

Thermal Technology Development Activities at the Goddard Space Flight Center - 2001

September 11, 2001

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Thermal Engineering Branch/Code 545

NASA/GSFC

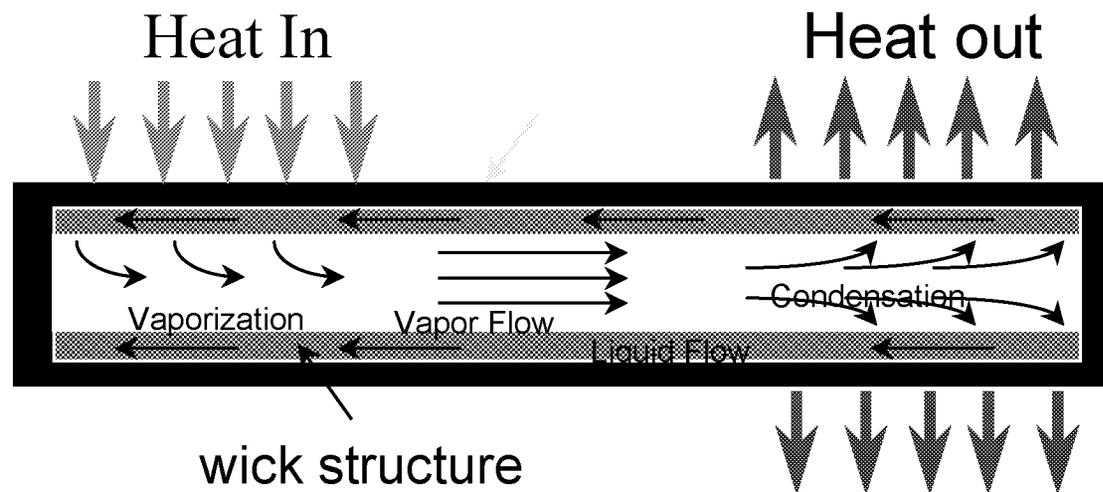
<http://watt-a-server.gsfc.nasa.gov/>

Thermal Technology Development at GSFC

- Two-Phase Systems
 - Heat Pipes and Variable Conductance Heat Pipes
 - Capillary Pumped Loops
 - Loop Heat Pipes
 - Vapor Compression Systems (Heat Pumps)
 - Phase Change Materials
- Variable Emittance Surfaces
- Advanced Coatings
- High Conductivity Materials
- Electrohydrodynamic (EHD) Thermal Control Systems

Heat Pipes

- Heat Pipes use capillary forces generated by a wick structure and the latent heat of vaporization of a working fluid to transfer large amounts of heat at nearly constant temperature
- Heat is input to one end of the pipe where it vaporizes the working fluid
- The vapor is transported to the condenser end of the pipe where it is condensed and the heat is rejected
- The condensed fluid travels back to the evaporator section in a capillary wick structure, which can be grooves in the wall, screens, sintered metal, or other porous material

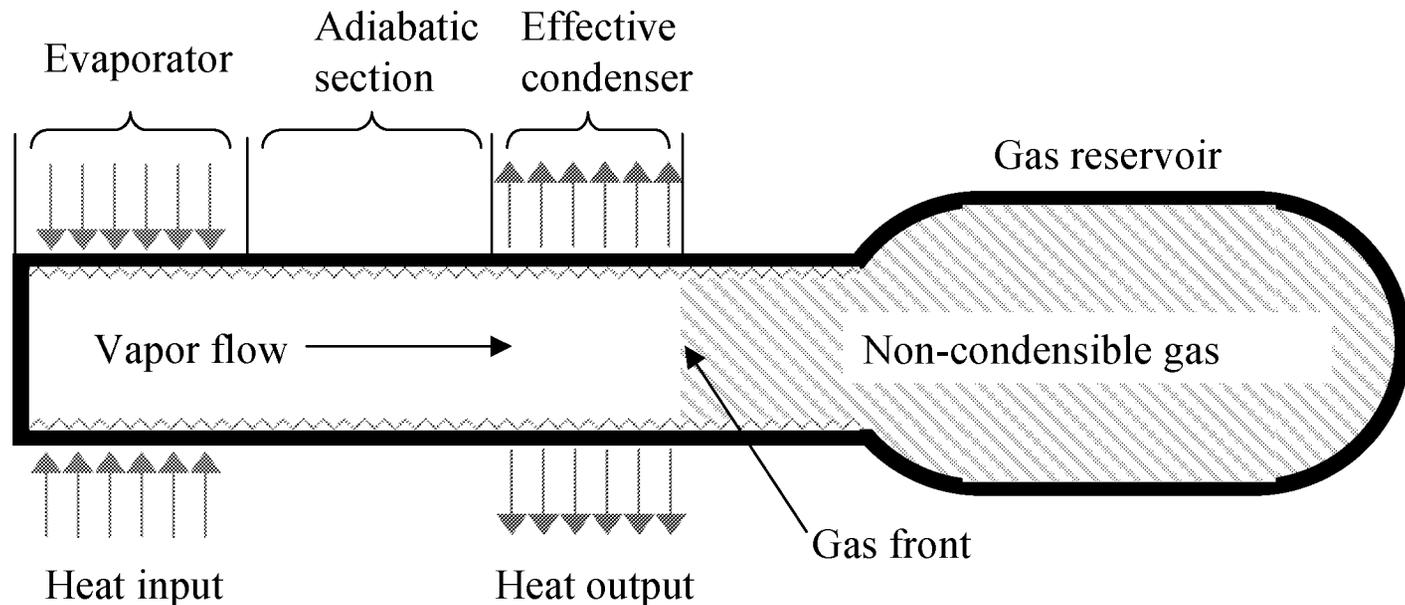


Heat Pipe Technology

1. Heat pipes are considered a standard off the shelf technology.
 1. Used routinely in many Spacecraft applications
 2. Copper/water pipes found in many laptops and video game consoles
2. Development efforts at GSFC
 1. Flight of HPP mid-deck experiment in early 90's, refinement of the GAP heat pipe analytical model
 2. Flight of cryogenic heat pipes on the shuttle in the mid 90's
 3. Qualification testing of Thermacore Copper/Water Heat Pipes in 2000
 1. Successfully completed Vibration and TV, including freeze/thaw cycles
 2. Promising diode action near 0 C as H₂O freezes, demonstrated restart under load - Ideal for electronics cooling
 4. Use of an ethane heat pipe for the Swift XRT instrument 2002, operates at -50 C with a 10 watt heat load

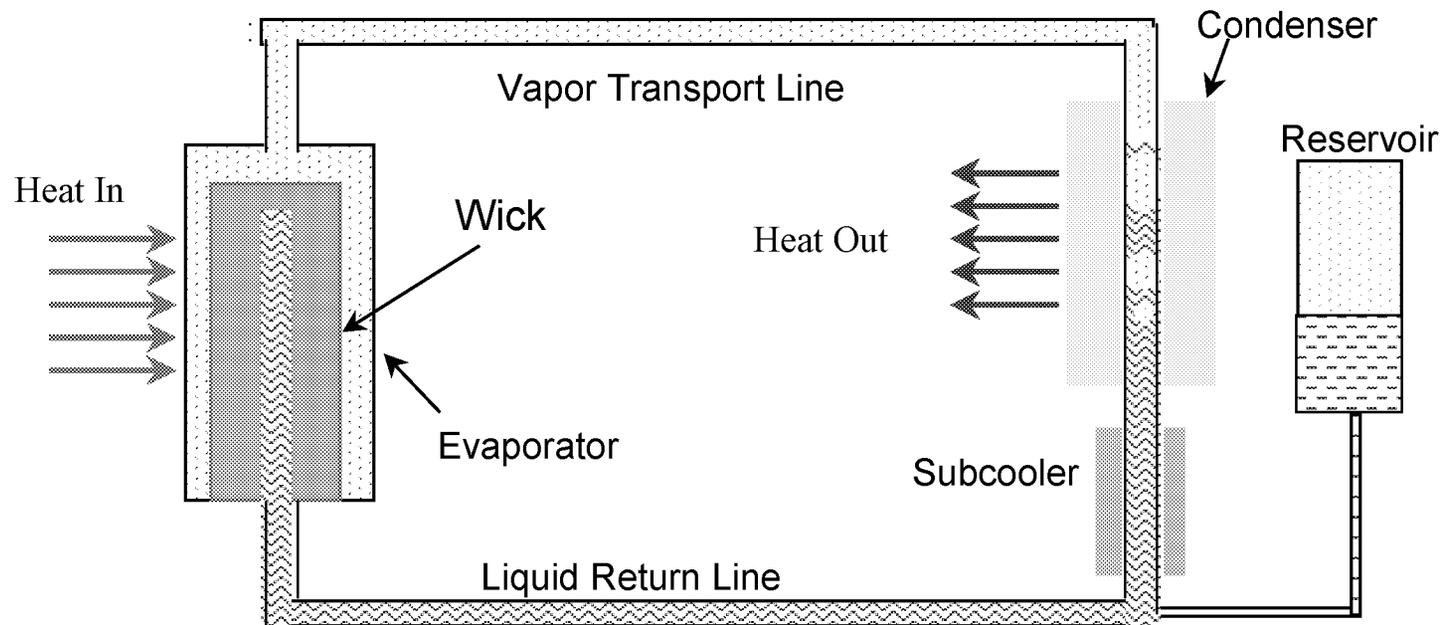
Variable Conductance Heat Pipes VCHP's

- VCHP's utilize a reservoir containing inert gas (nitrogen) to block part or all of the condenser, thus providing temperature control of the heat pipe to $\pm 2\text{ C}$
- Requires electrical controller and heater on the reservoir, linked to a feedback thermistor
- VCHP's are off the shelf technology, but not extensively used
- GSFC applications on TPF flight experiment and Swift Loop Heat Pipe



Capillary Pumped Loops

- Capillary pumped loops (CPL's) are two-phase heat transfer devices which use capillary forces for heat acquisition and fluid pumping with no moving parts
 - Transfers high heat loads over long distances with vibration free operation and passive control
 - Factor of 30x improvement in wicking height over conventional heat pipes - greatly improves ground testability and eases spacecraft integration
 - Diode action offers shut down capability, minimize heater power requirements

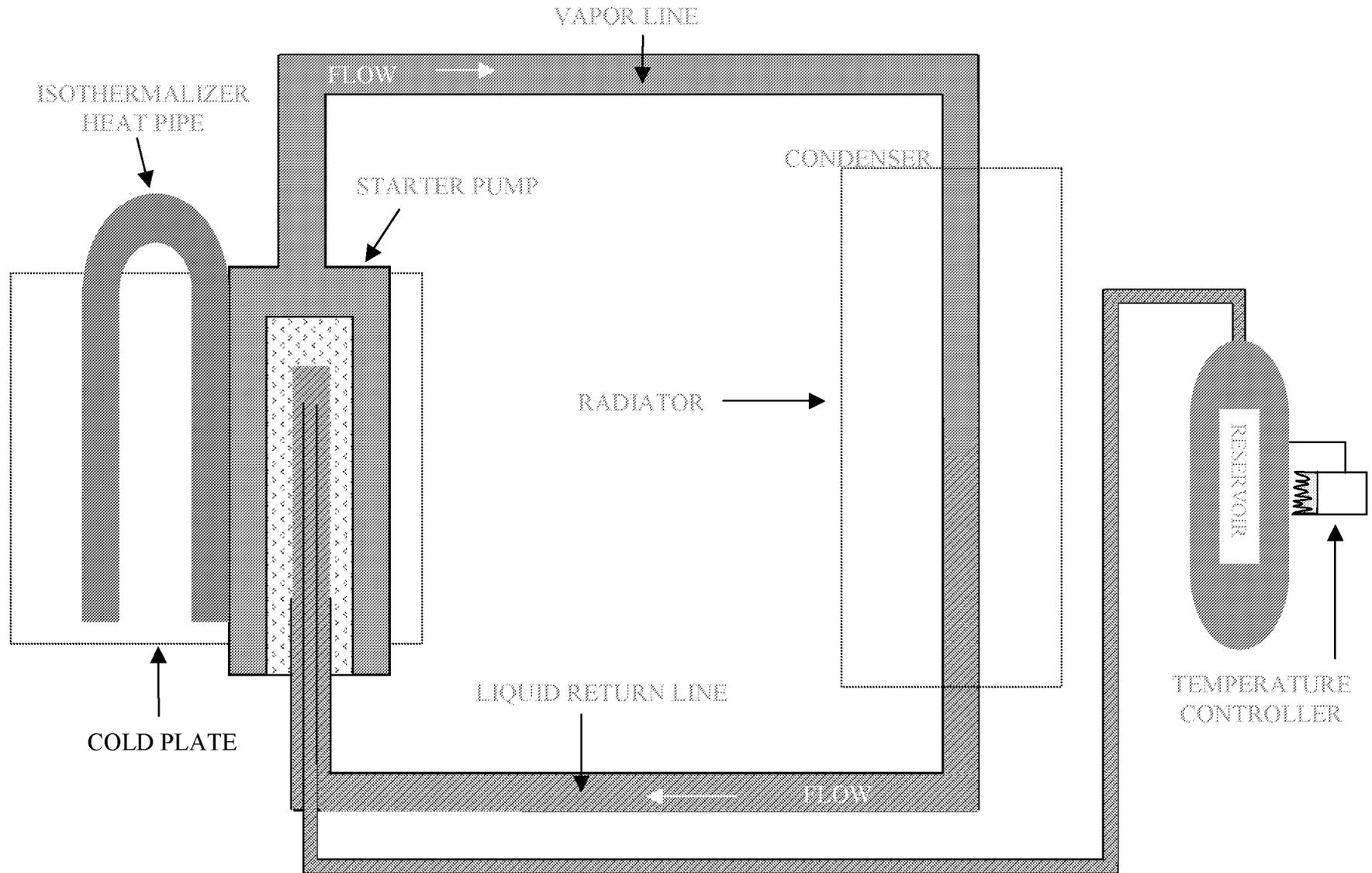


Capillary Pumped Loop Technology

CPL

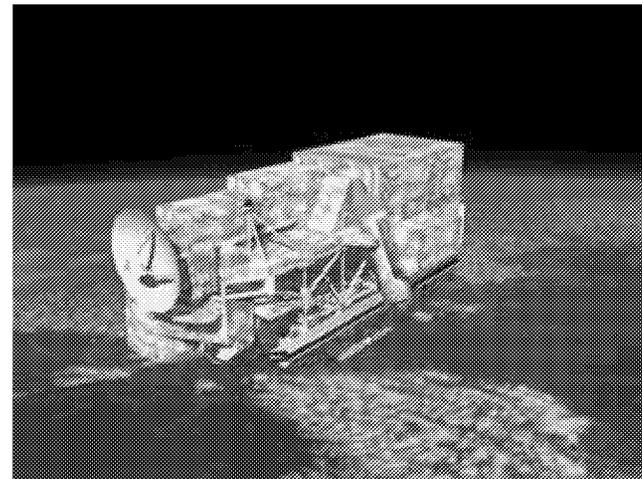
- CPL concept originated at the Lewis Research Center
- Developed at GSFC starting in the early 80's
- Numerous test beds and shuttle flight experiments
 - CPL GAS and Hitchhiker flight experiments in 1985 and 1986
 - Proof of Concept
 - CAPL 1 and CAPL 2 flight experiments in 1994 and 1995
 - Point Design for the EOS-AM (now TERRA) Spacecraft
 - Single pump CPL verified for flight applications - “Starter Pump CPL”
 - TPF Flight Experiment in 1997
 - Proof of Concept for multiple pump loop
 - Multiple pump CPL's
 - CAPL 3 flight experiment manifested on STS-108, Nov 2001
 - CCQ flight experiment (awaiting flight opportunity)

Starter Pump Capillary Pumped Loop

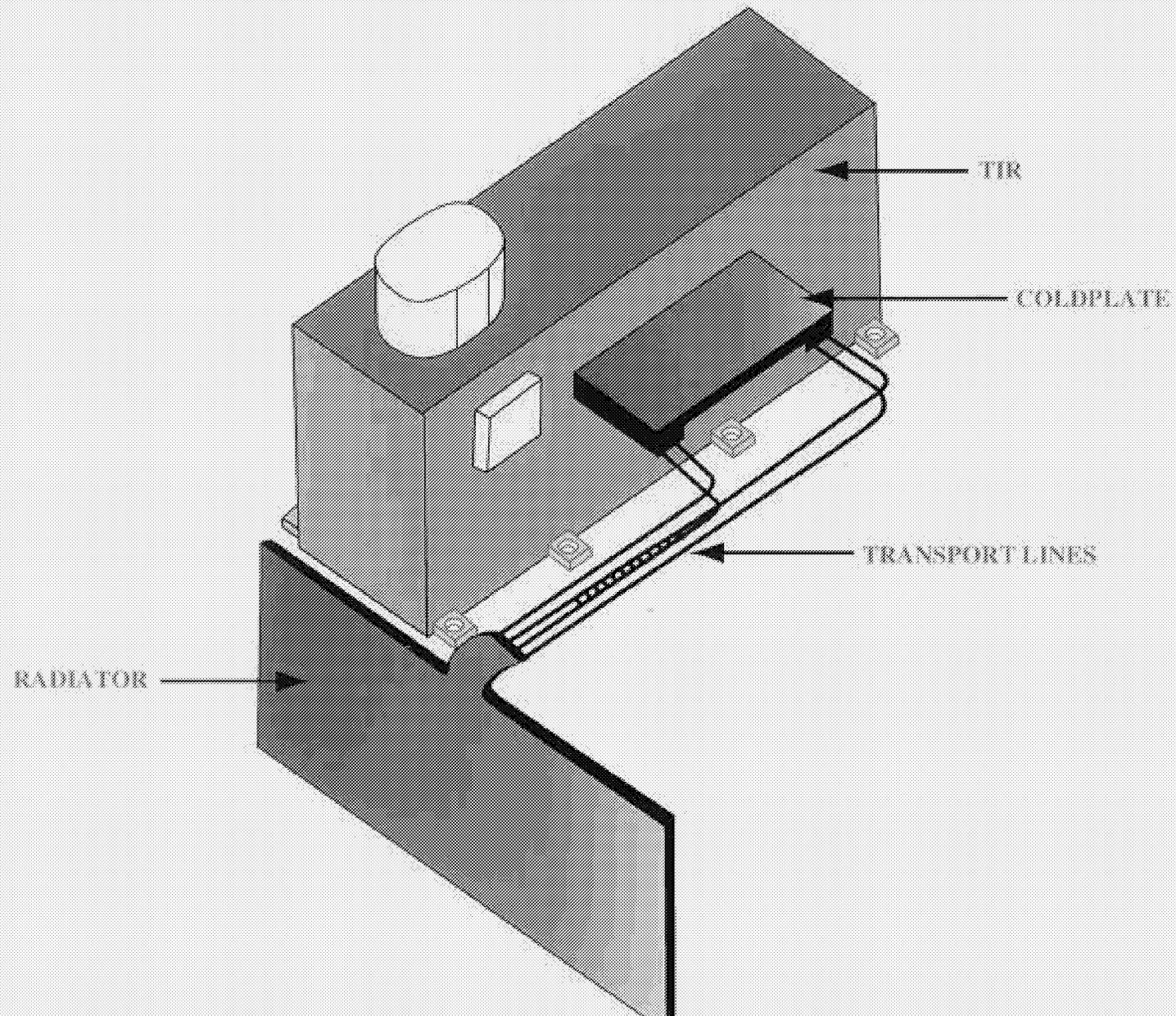


CPL's on TERRA (EOS-AM)

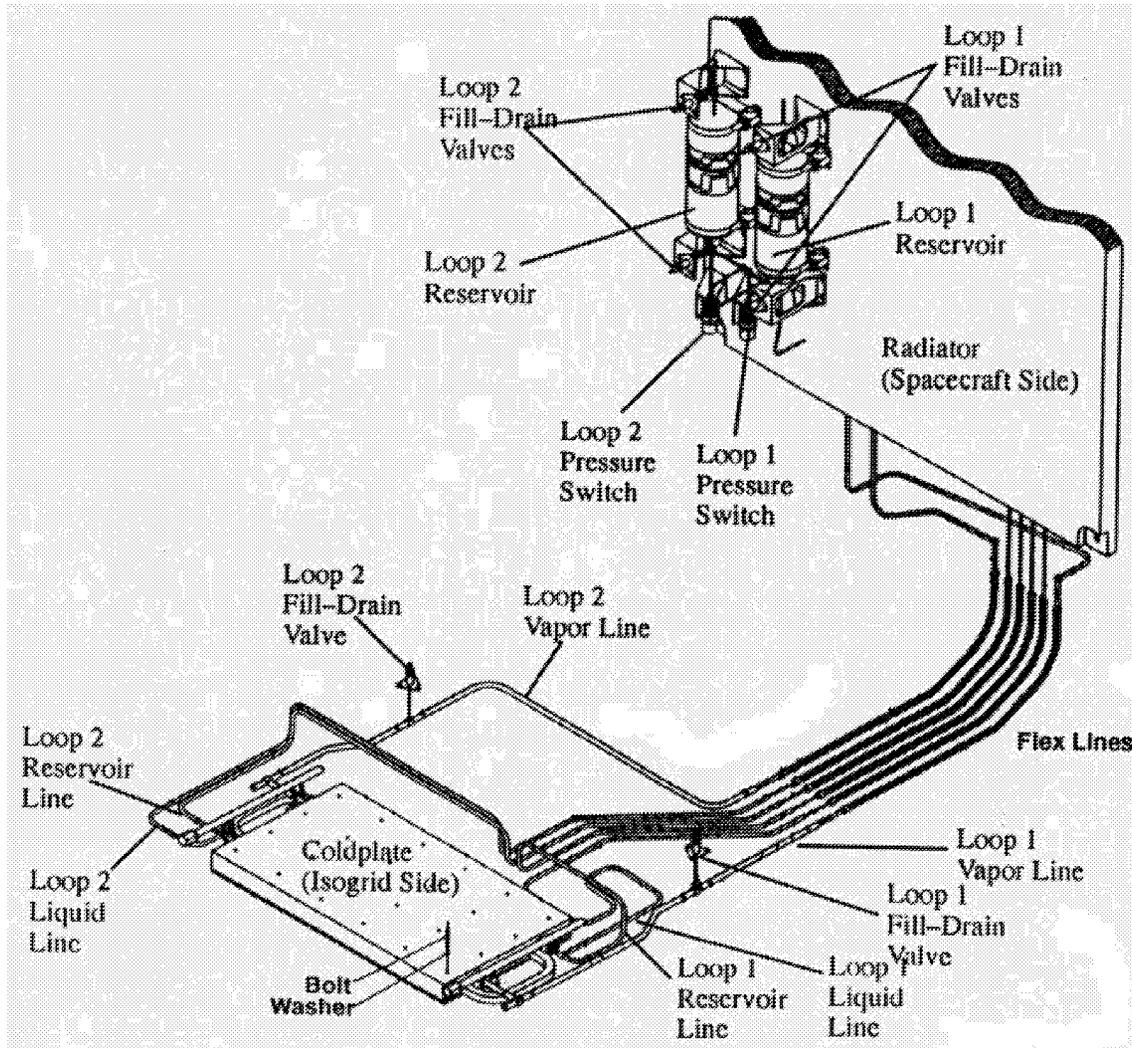
- Terra launched December 18, 1999
- Two-phase loops (CPLs) are on SWIR, TIR and MOPITT instruments
- On the next day, the first CPL system in a flight mission was started successfully.
- All 3 CPLs continue to demonstrate reliable, stable thermal control for their instruments



ASTER - TIR CPL CONFIGURATION

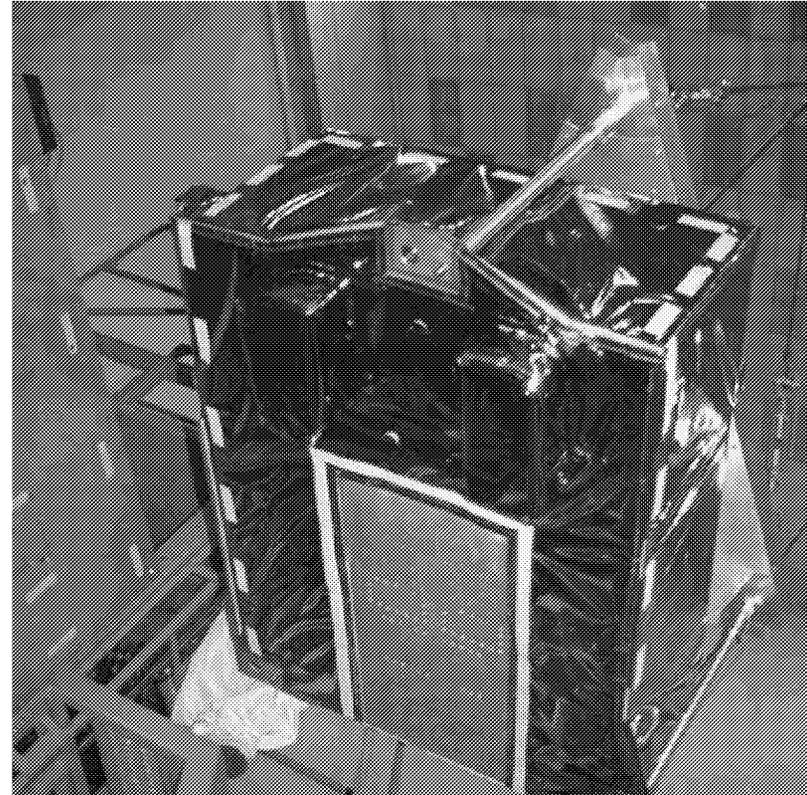
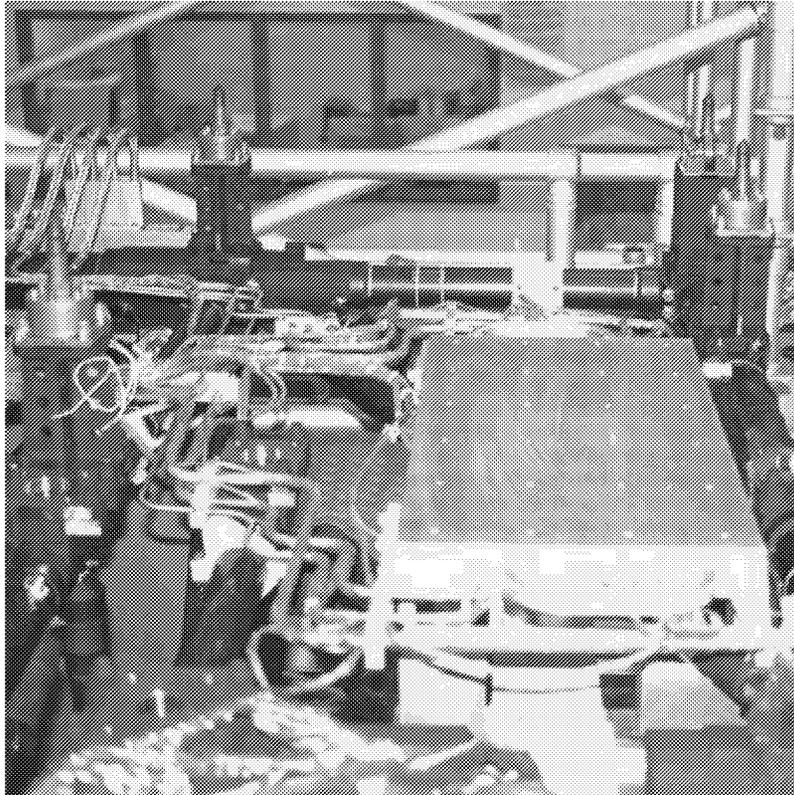


TERRA CPL Typical Layout



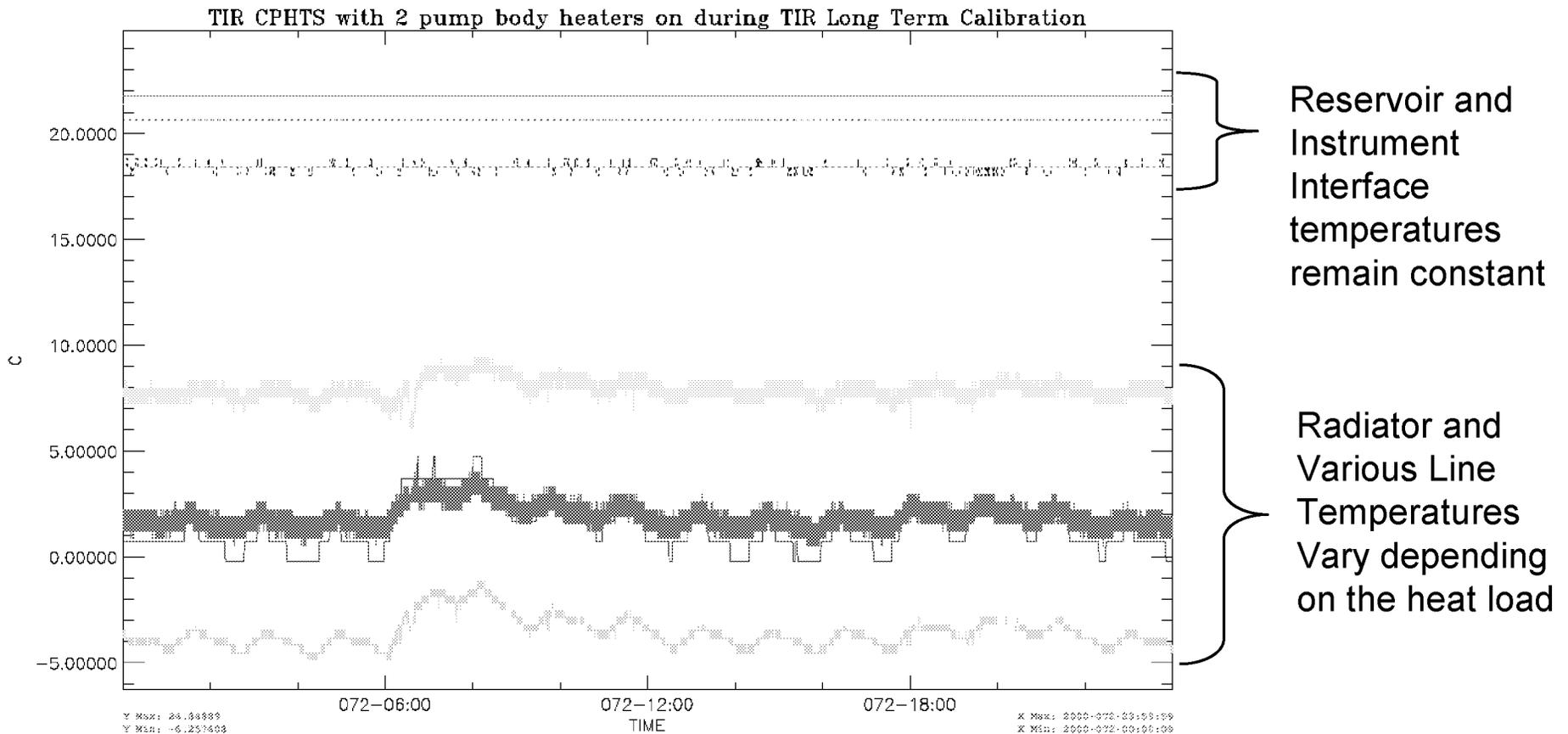
TERRA CPL - Coldplate

- Coldplate provides the thermal sink for the instrument.
- Contains the Capillary Starter Pump (Evaporator) that provides the capillary pumping head via porous wick.

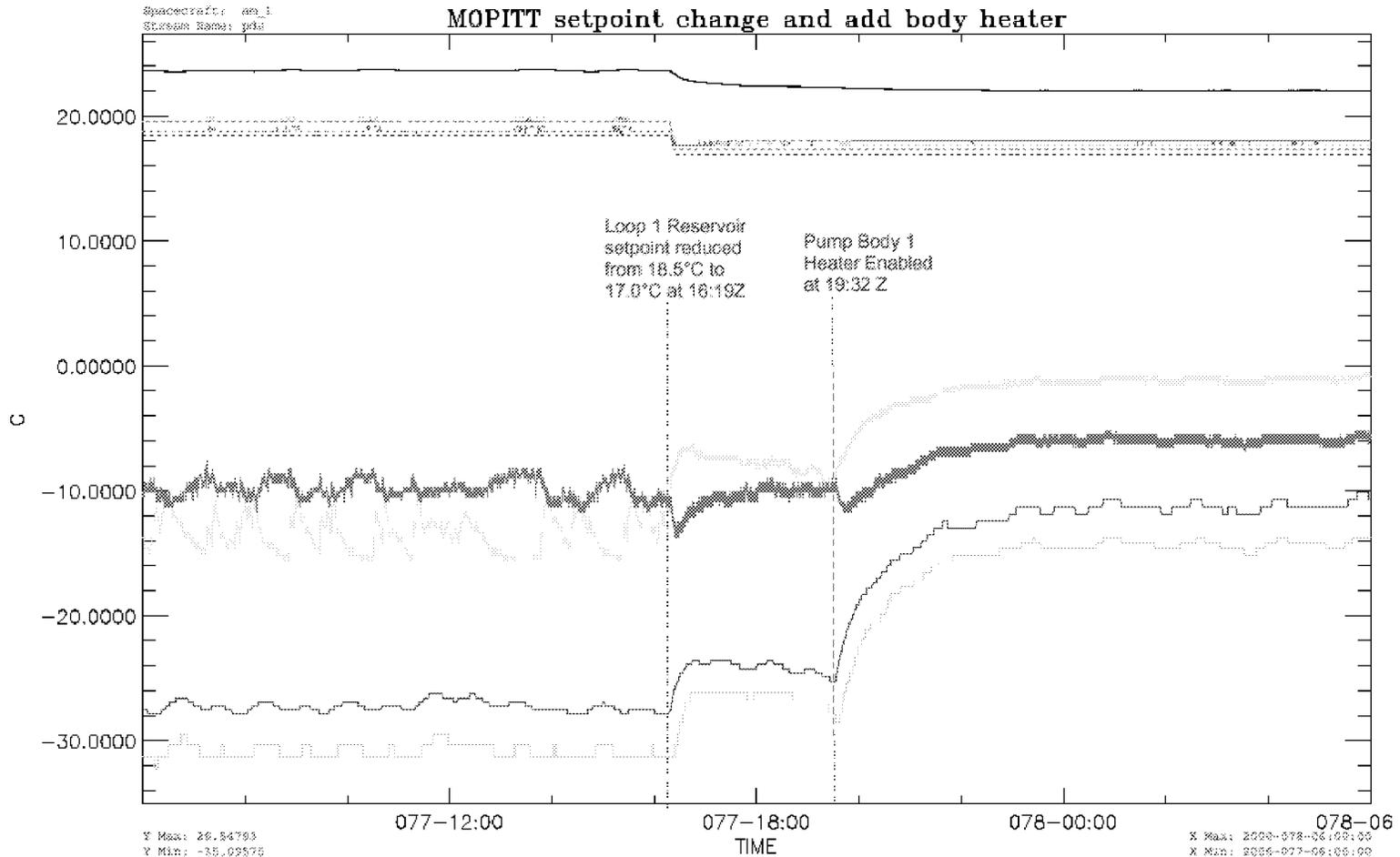


TERRA Normal Operations

The Radiator, Liquid Lines and Reservoir Lines have orbital variations and vary depending on the instrument activities. The coldplate remains at a constant temperature during all activities.



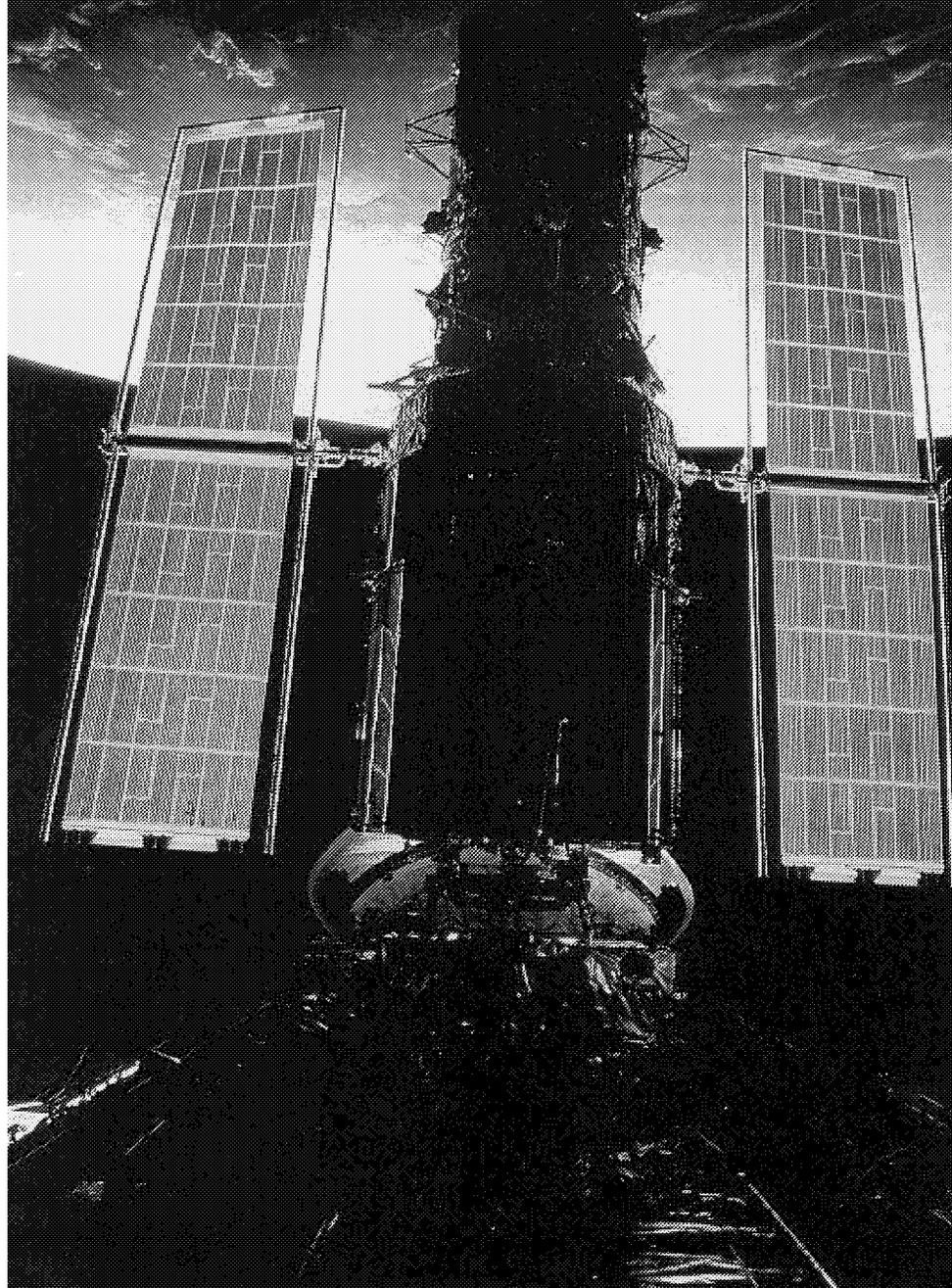
Reservoir Setpoint Change



MEMORIC NAME	SAMPLES	MINIMUM	MAXIMUM	AVERAGE	STD DEV	DESCRIPTION
MOP_TR_RPLT_2	10947	21.780	23.740	22.693	0.76298	Base Plate, Temperature S [C]
TCS_TR_N_RESV_LOOP1	10947	17.989	19.947	18.662	0.74368	MOPITT Loop 1 Reservoir N [C]
TCS_TR_M_RESV_LOOP1	10947	17.989	19.947	18.662	0.74368	MOPITT Loop 1 Reservoir M [C]
TCS_TR_M_RESV_LOOP1	10947	-27.879	-19.042	-20.466	7.2311	MOPITT Radiator Surface M [C]
TCS_TR_M_RESV_LOOP1	10947	-27.879	-19.042	-20.466	7.2311	MOPITT Loop 1 Reservoir M [C]
TCS_TR_M_RESV_LOOP1	10947	-15.772	-8.1761	-11.964	2.6118	MOPITT Loop 1 Reservoir M [C]
TCS_TR_M_RESV_LOOP1A	10947	16.998	18.784	17.557	0.74368	MOPITT Loop 1 Reservoir T [C]
TCS_TR_M_RESV_LOOP1B	10947	17.184	19.129	17.948	0.74584	MOPITT Loop 1 Reservoir T [C]
TCS_TR_M_RESV_LOOP1C	10947	17.433	19.387	18.120	0.74198	MOPITT Loop 1 Reservoir T [C]

Current Time: 2008-080-13:19:16
 Req Start Time: 2008-077-09:00:00
 Req Stop Time: 2008-078-06:00:00
 Sample Rate: All Points
 Profile Name: mopl_resvAR.abc
 User Name: abcuser

HST

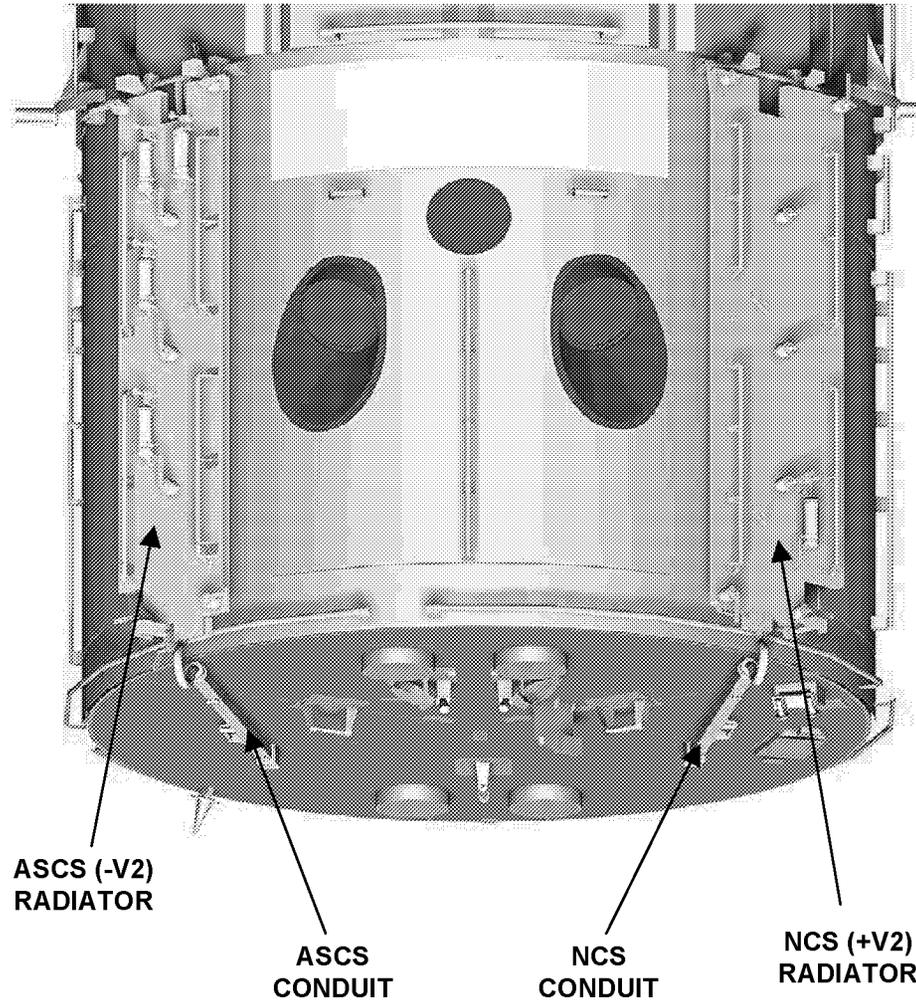


HST SM 3B Servicing Mission

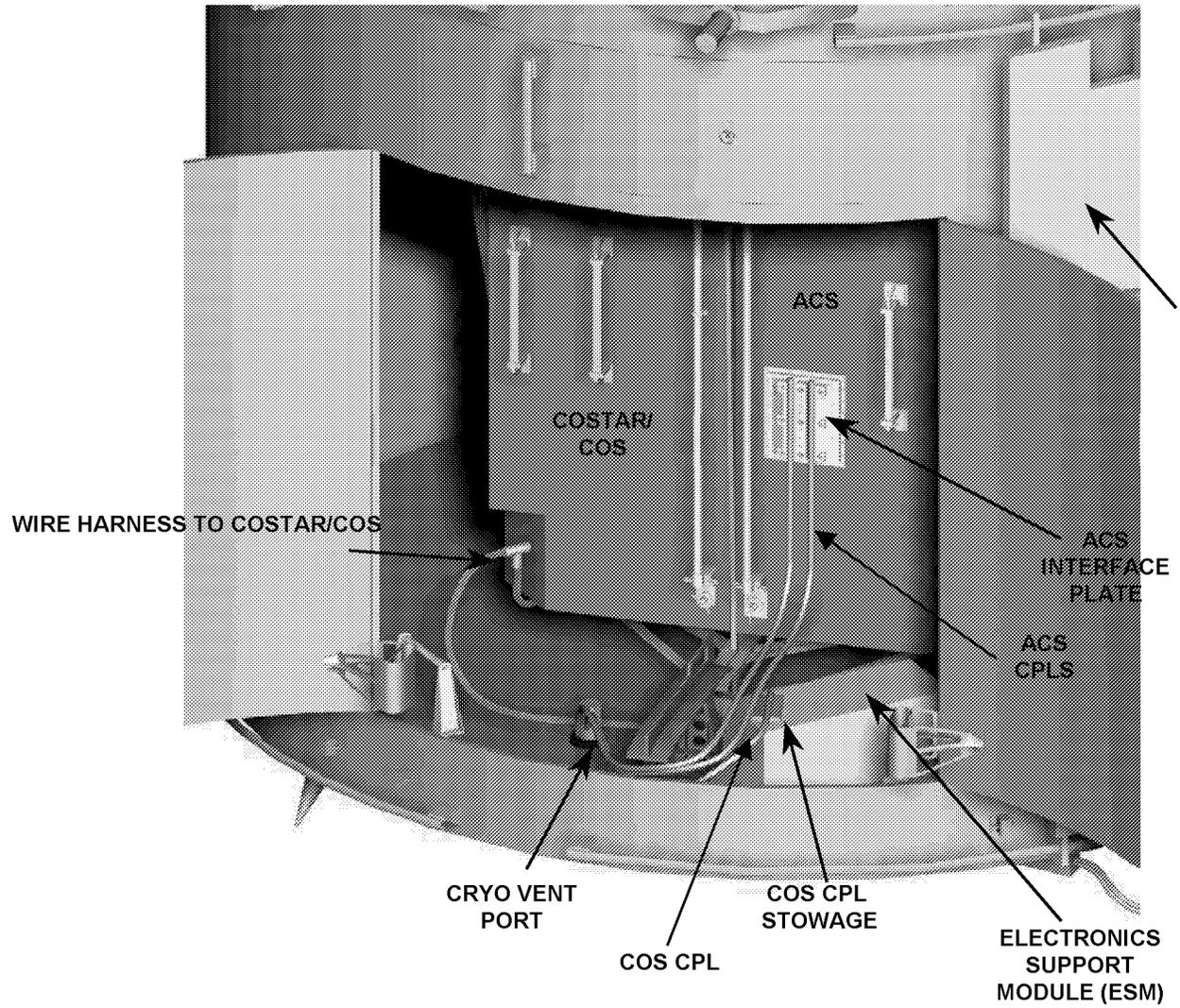
STS - 109 Jan 2002

- **Near Infrared Camera and Multi Object Spectrometer (NICMOS) instrument installed on HST during Servicing Mission 2, Feb 1997**
 - Detectors cooled by nitrogen ice contained in a dewar
 - Thermal short in dewar detected shortly after SM2
 - Expected NICMOS lifetime of 4.5 years shortened to 1.7 years
- **On SM 3B, the astronauts will install a brayton cycle, mechanical cryo-cooler to cool NICMOS detectors and resume operations**
 - Mechanical refrigerator must be capable of developing in excess of 7 watts of cooling power at 70 K
 - Flexible Capillary Pump Loop built by Swales Aerospace selected to transfer energy from cryocooler to external radiator
- **Precursor check-out mission (HOST) flown on STS-95 in October 1998 to verify cryocooler and CPL operation in micro-gravity - Highly Successful.**

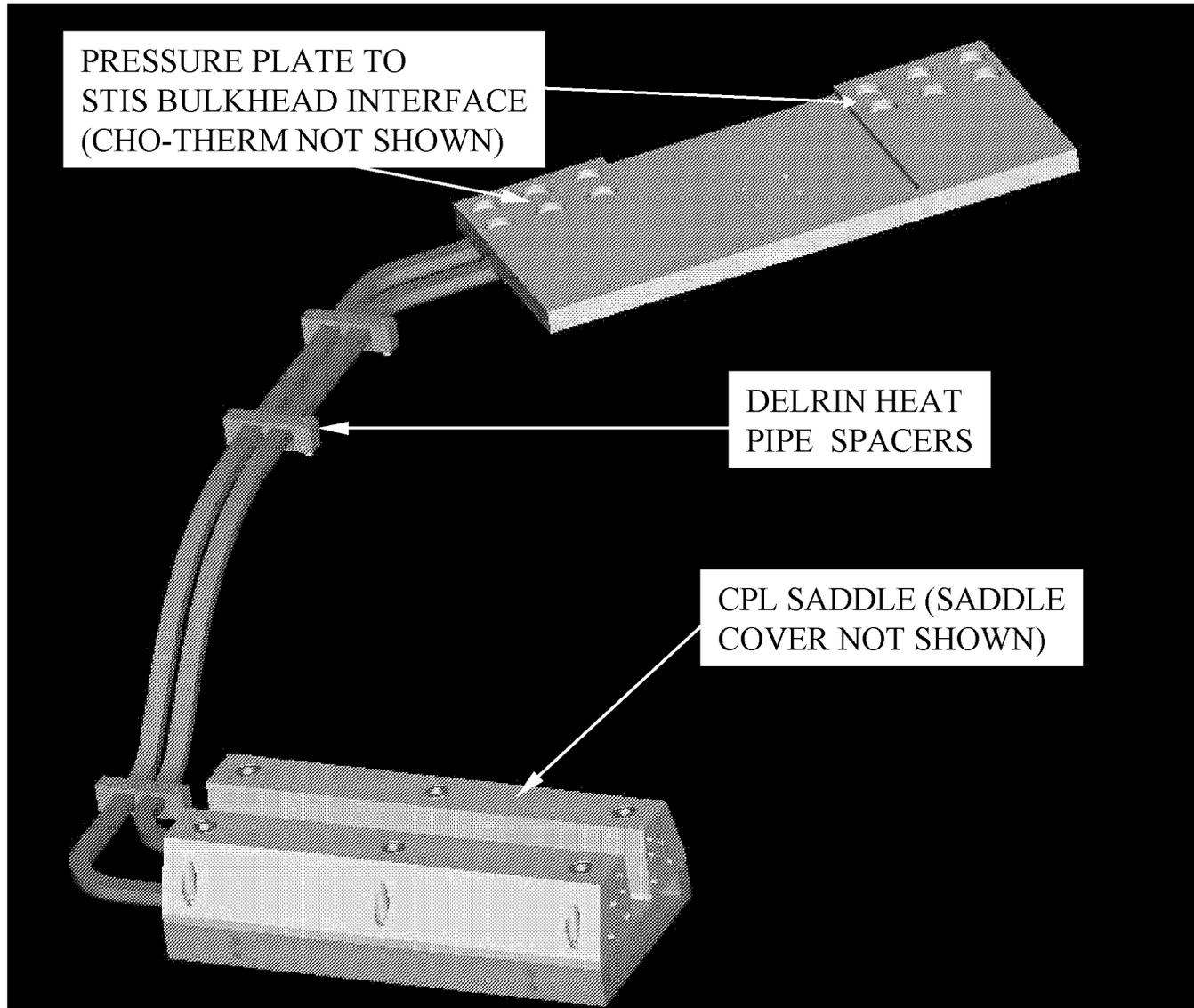
HST with CPL Radiators



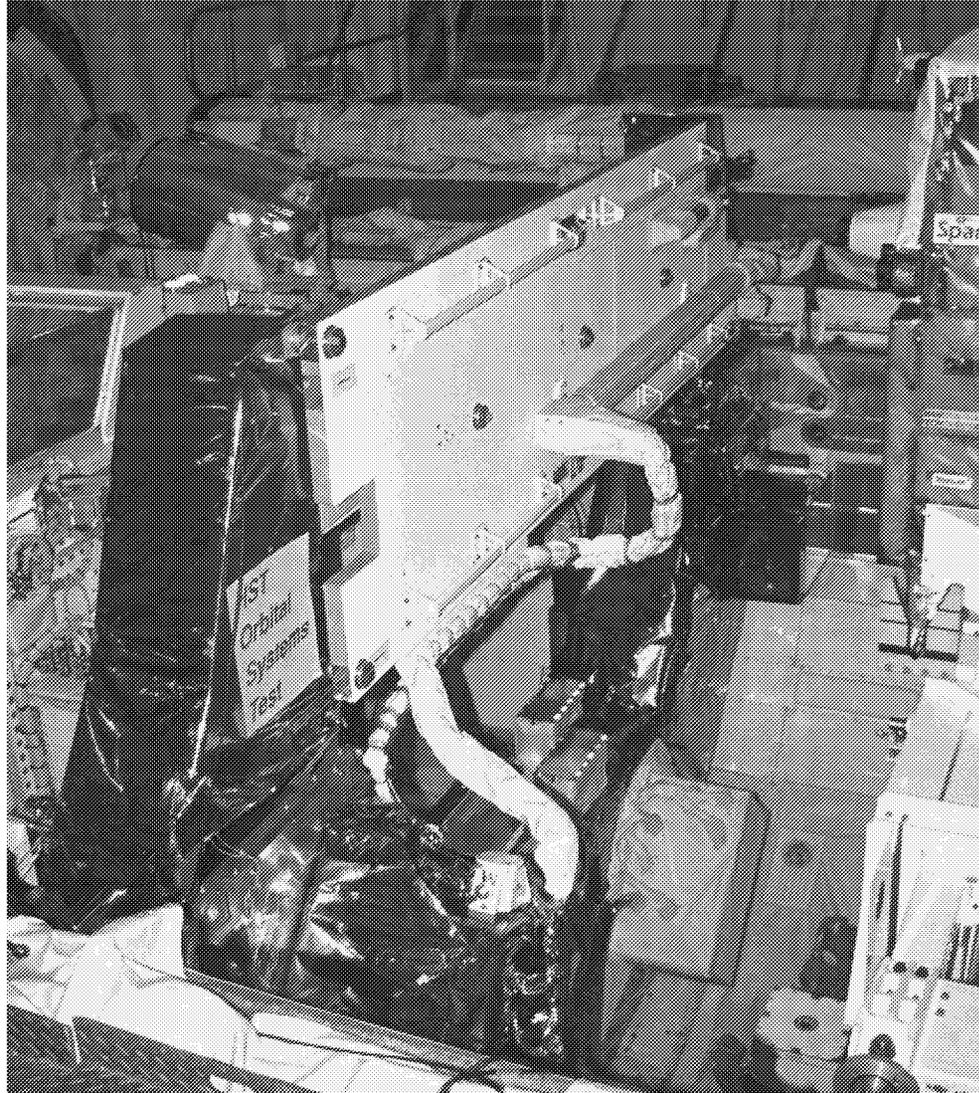
HST with CPL Installed



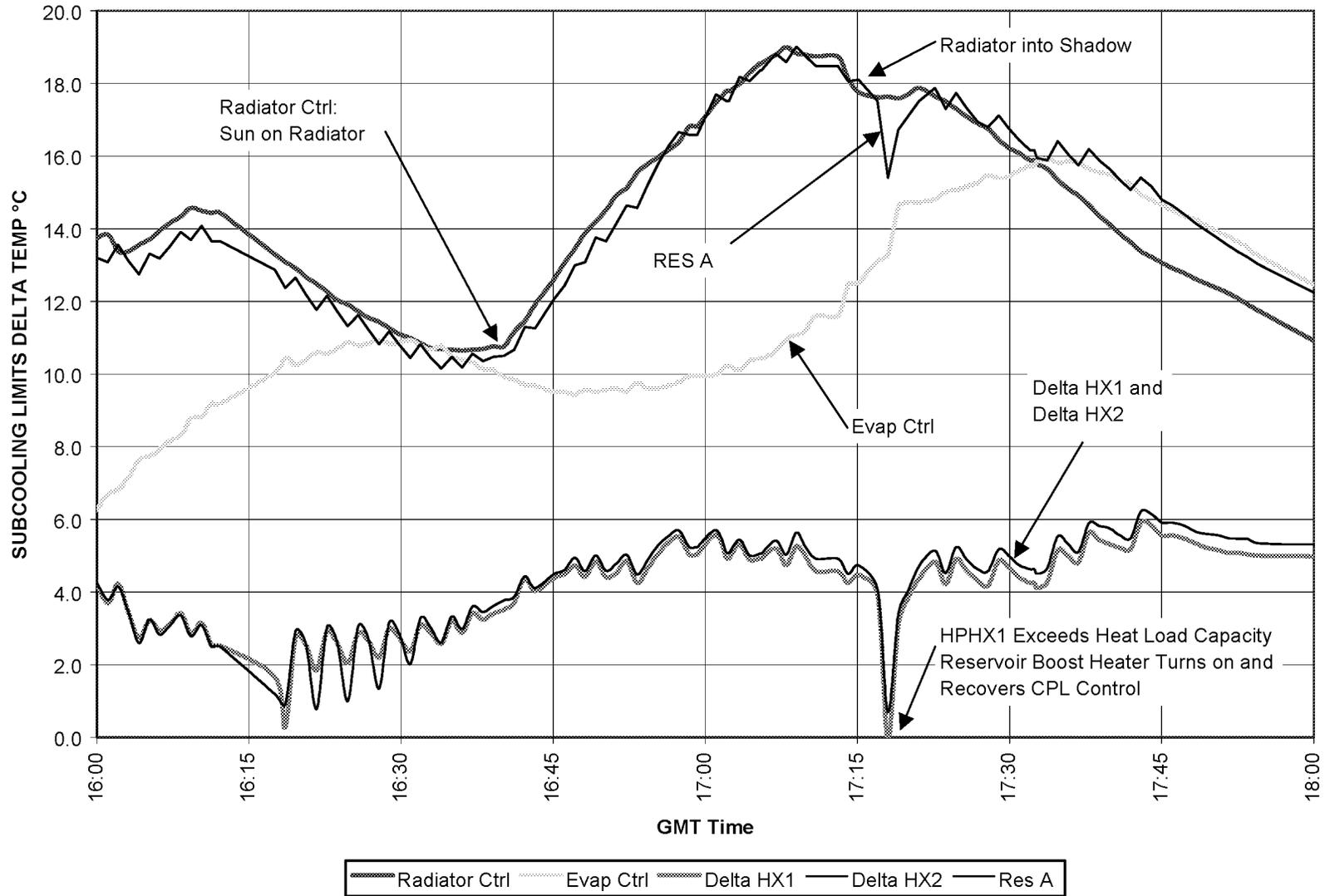
HST Thermal Components Assembly



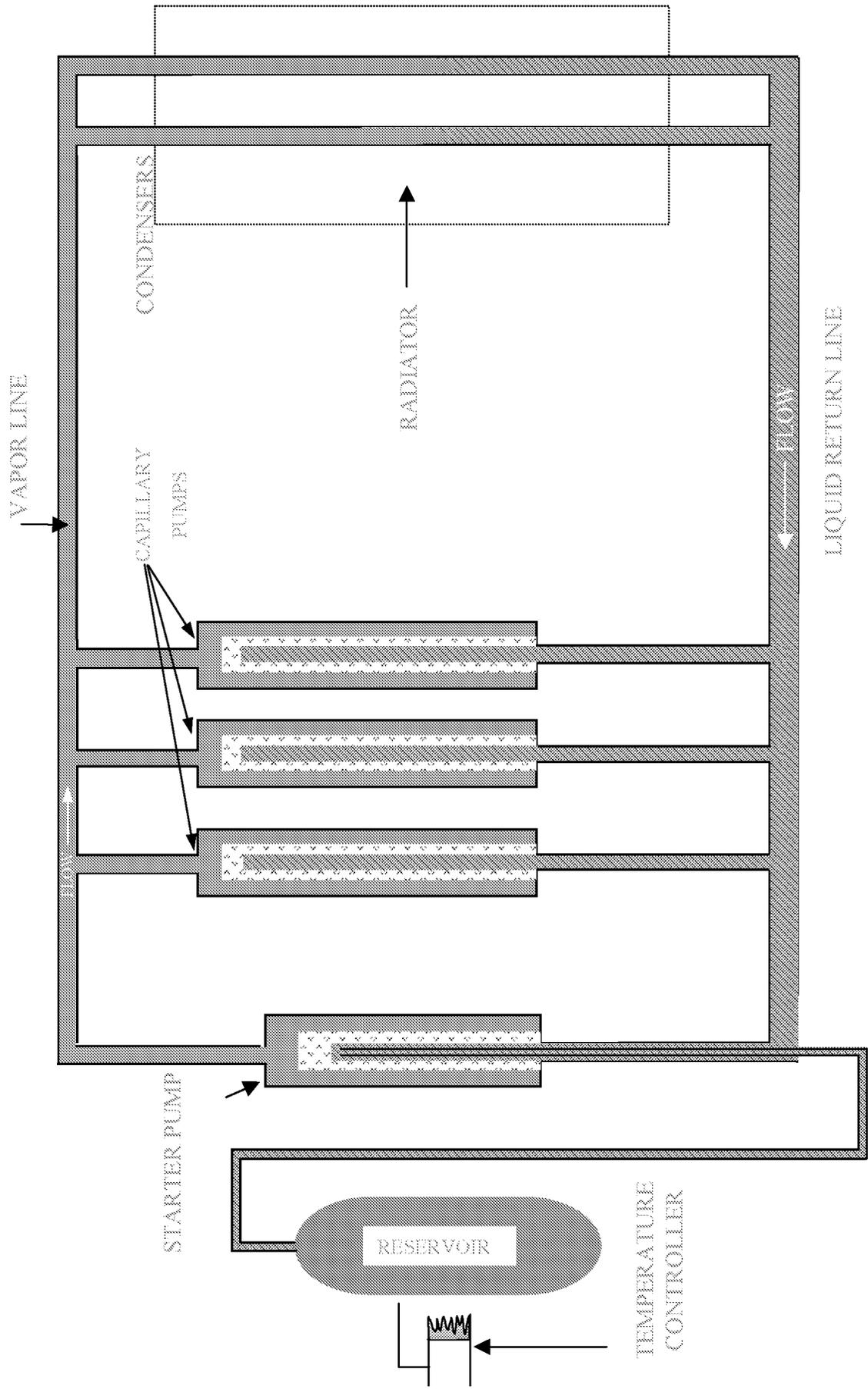
HOST Carrier Installed in the Payload Bay



CPL Temperature Control Law Response



Multiple Evaporator Capillary Pumped Loop



CAPL 3 Flight Experiment

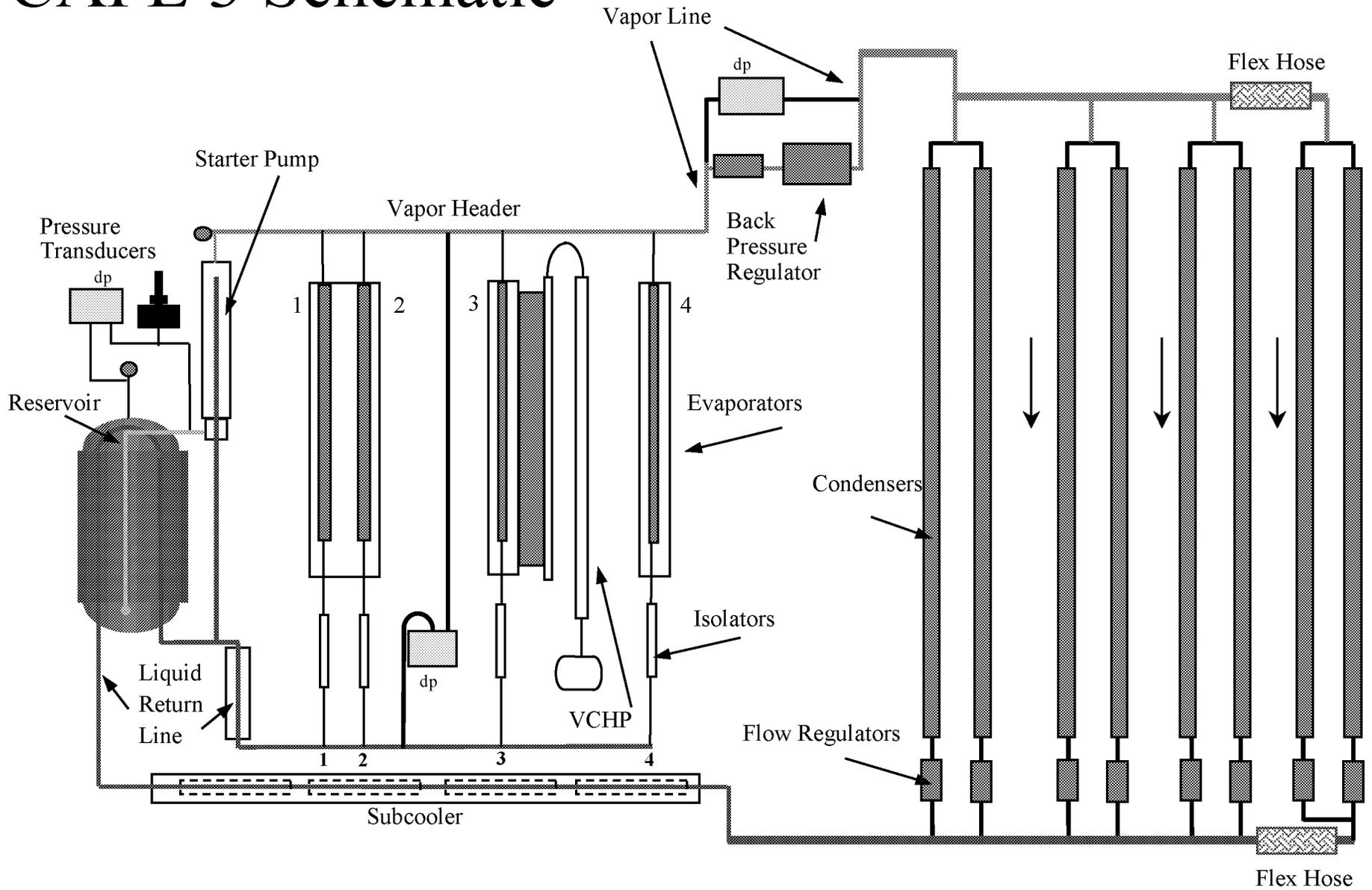
NRL/NASA Experiment



CAPL 3 Flight Experiment

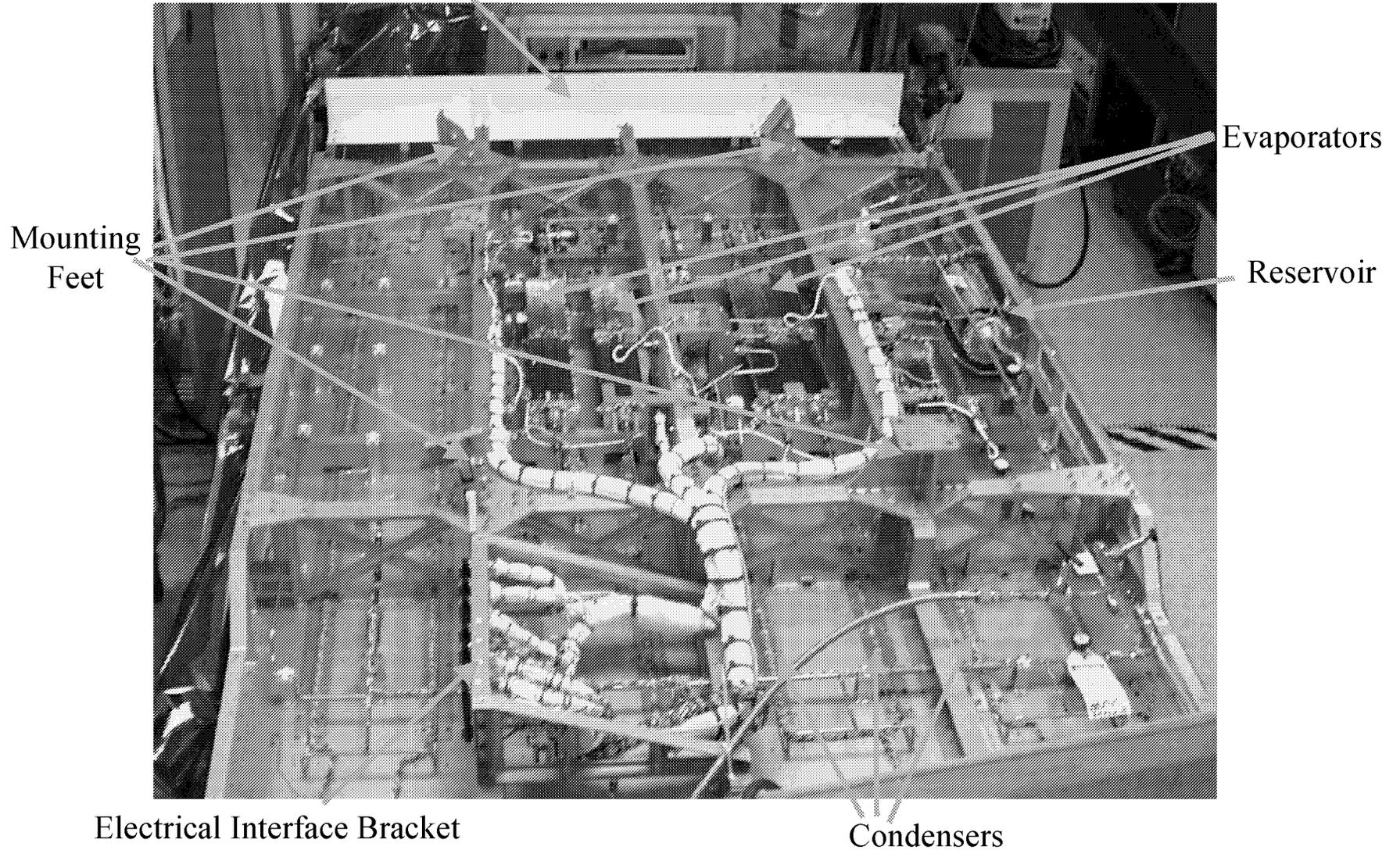
- Follow on to CAPL 1 (STS-60, 2/94) and CAPL 2 (STS-69, 9/95) flight experiments
- Joint Naval Research Lab (NRL)/NASA partnership which will meet technology objectives for both the Department of Defense and NASA
- Two-phase ammonia thermal control system consisting of a capillary pumped loop with multiple capillary evaporators and parallel direct condensation radiators
- Includes a capillary starter pump and a back pressure regulator to assist with start-up in micro-gravity
- Will demonstrate heat load sharing between evaporators which provides heating from the loop as well as cooling
- Currently manifested on STS-108 in Nov 2001

CAPL 3 Schematic

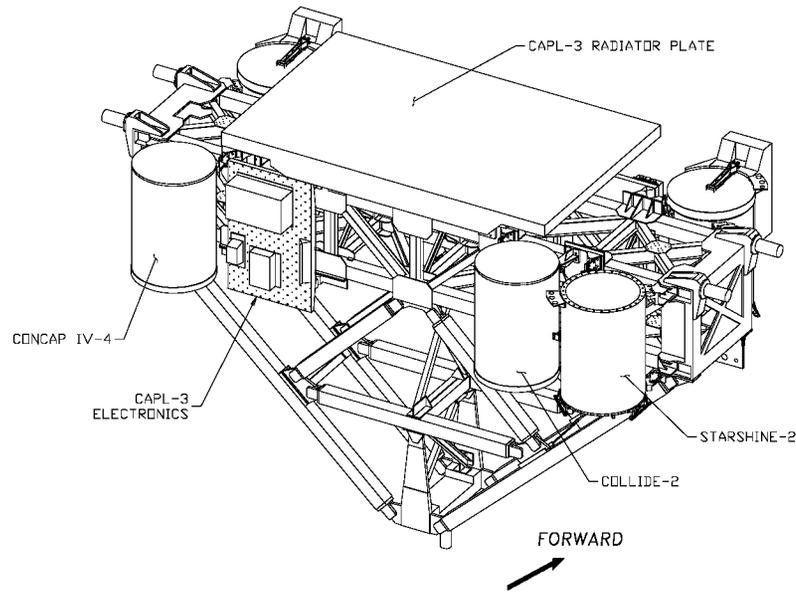


CAPL 3 Radiator Assembly (Upside Down)

Subcooler Radiator

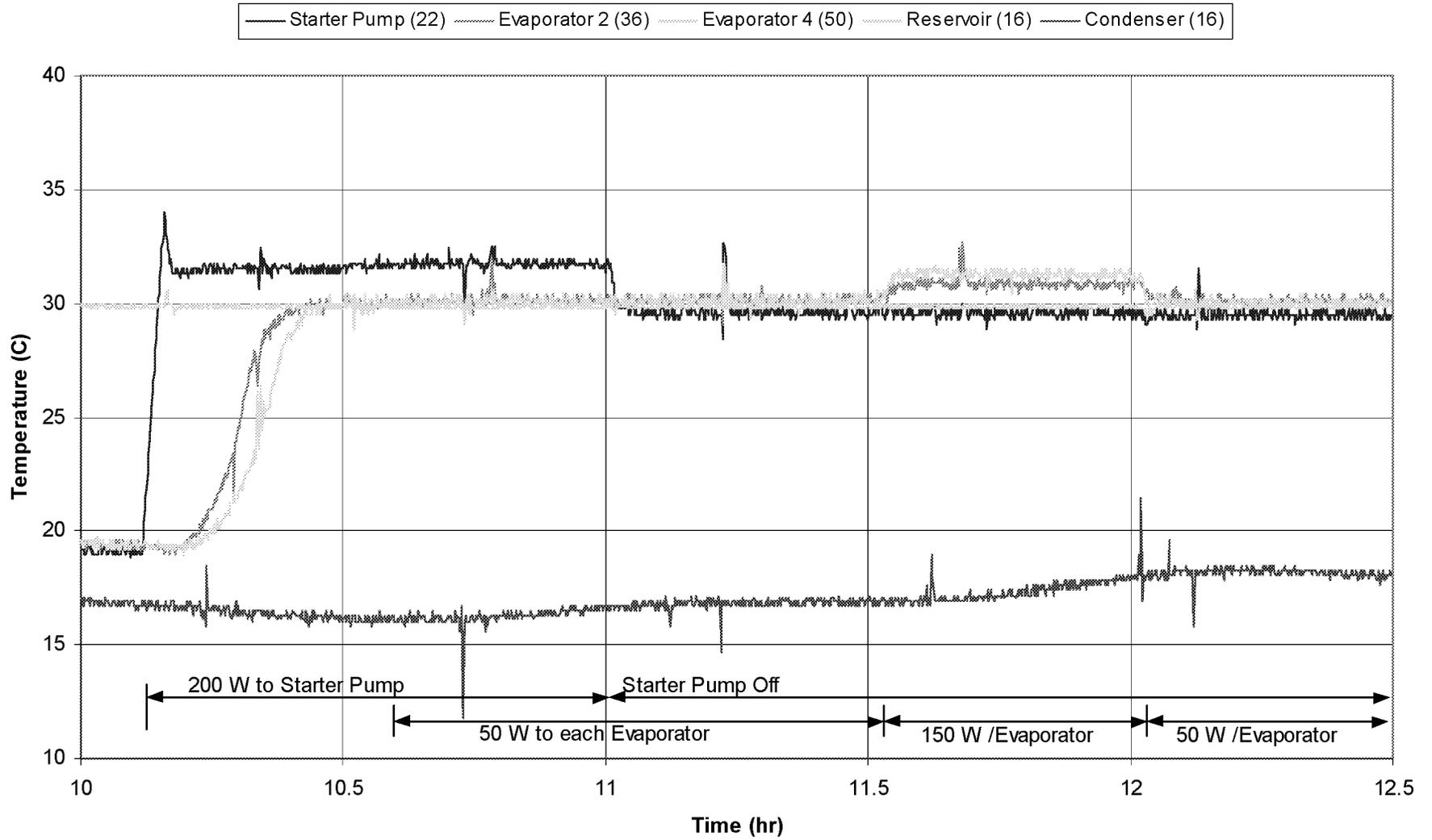


CAPL 3 Mission Description



- Mounted aboard GAS bridge structure inside the shuttle bay
- 72 hour mission duration requested in SF1628
- Nominal power: 800 W, max power approximately 1600 W
- GSFC POCC for real-time Hitchhiker payload operation
- Shuttle bay nadir facing (-ZLV), or colder orientation, for at least 54 hours required, with 18 hours in bay to space attitude requested

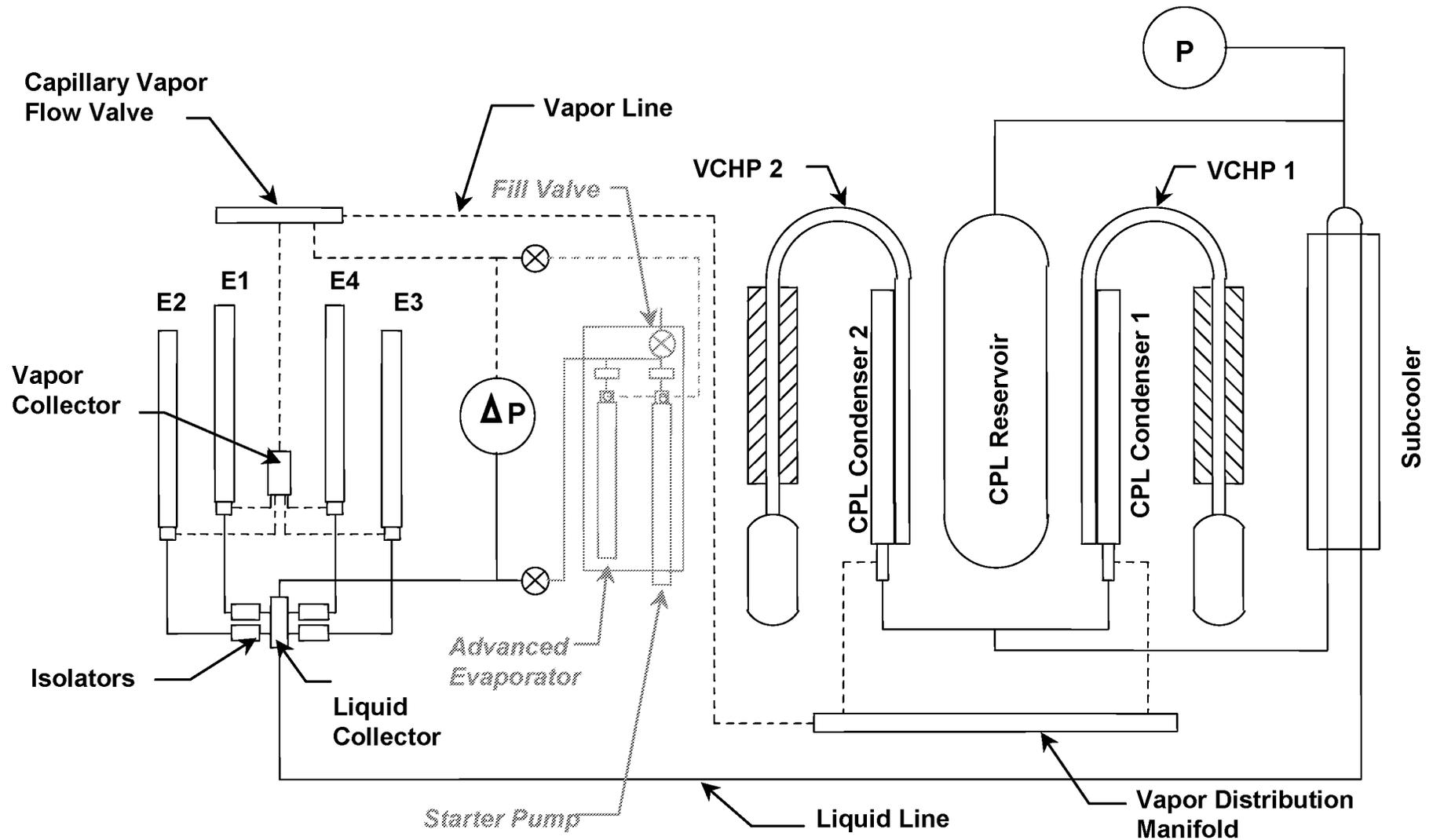
CAPL 3 Ambient Testing - 1/8/99 Start Up



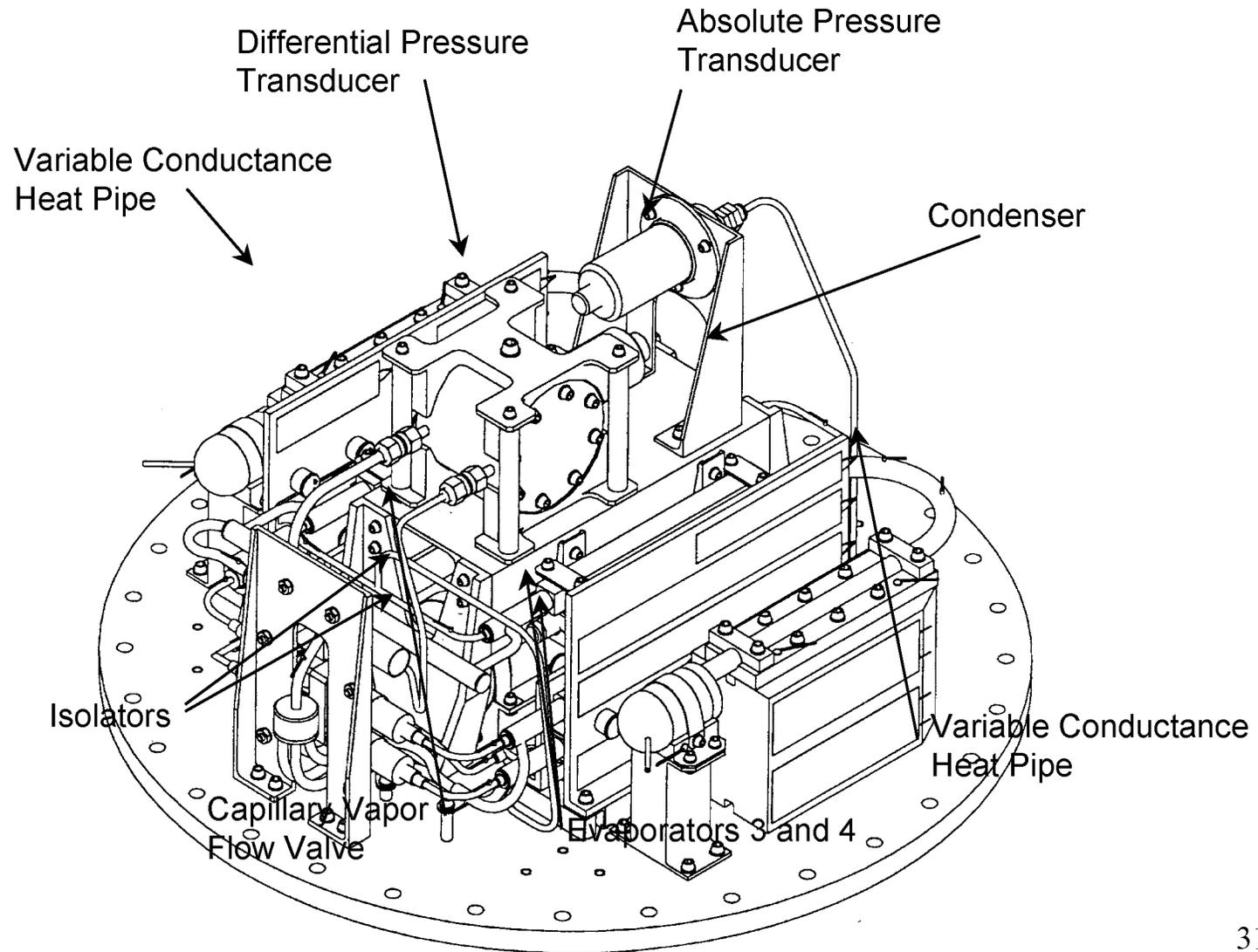
CCQ Objectives

- **Modify Two Phase Flow (TPF) experiment, flown in 1997**
 - Demonstrate proposed TRW CPL on the Shuttle using TPF CPL with an added evaporator and a capillary starter pump
 - Test new evaporator containing advanced wick which prevents vapor blow-by (Air Force Development) and increases pumping capability
 - Test mini-Loop Heat Pipes built by the Russians and provided by the Air Force
- **WHAT ARE WE GOING TO SHOW?**
 - High reliability CPL system suitable for use in spacecraft applications
 - Provide flight verification of mini-LHP design
- **WHEN?**
 - Actual flight date will depend on manifesting availability

TPF/CCQ Schematic

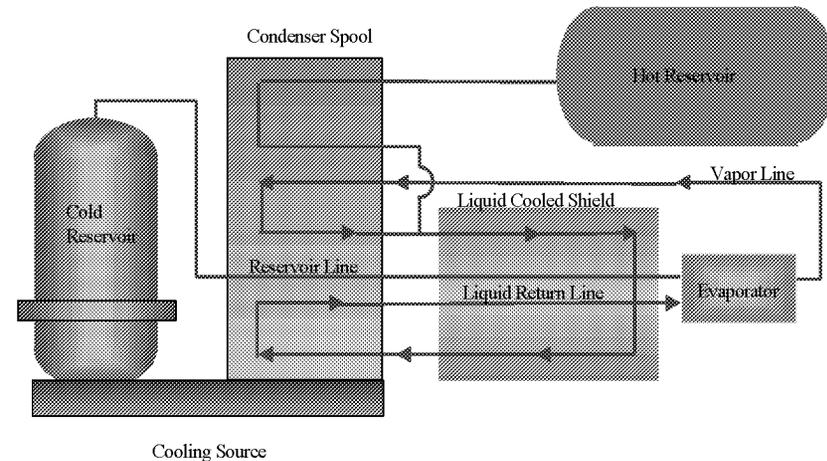


TPF Layout on Canister Lid



Cryogenic Capillary Pumped Loop (CCPL)

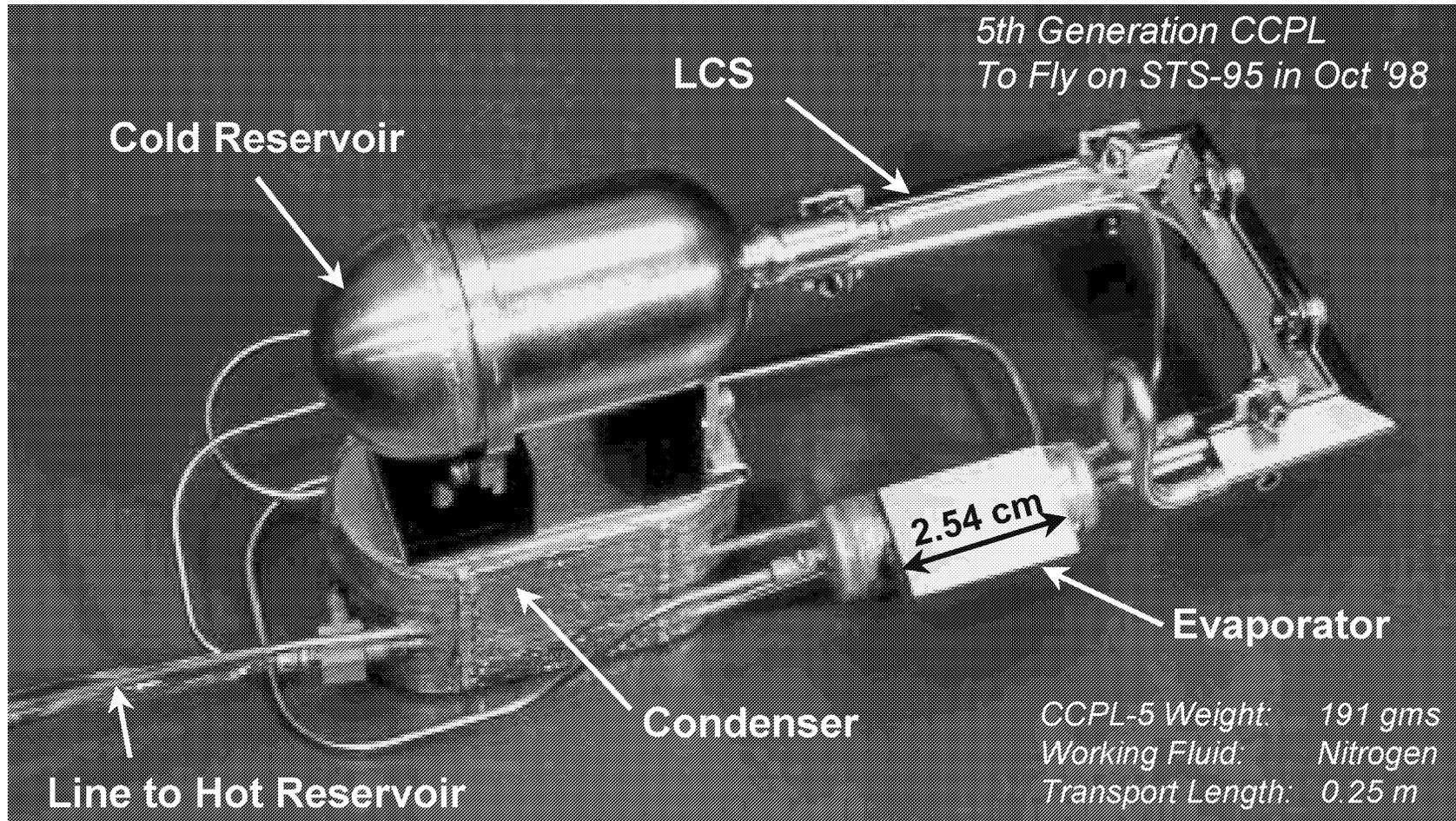
Capillary Pumped Loops (CPLs) are capable of transporting large amounts of heat over long distances and provide tight temperature control. They utilize capillary pumping forces (no moving parts).



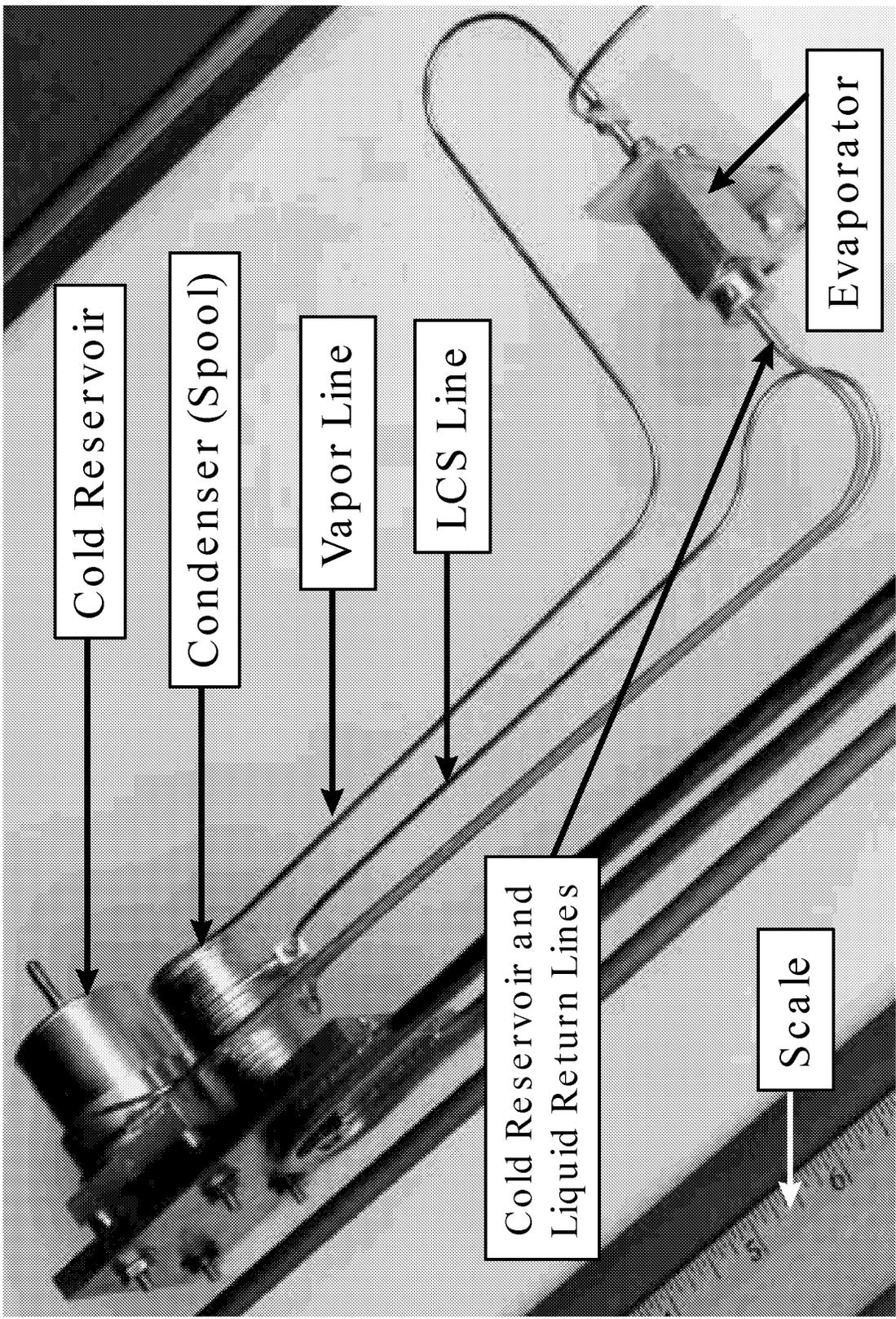
- Several Cryogenic CPL's have been developed and tested
 - Transport of 0.5 to 12 watts in 80 to 100 Kelvin range with Nitrogen
 - Transport of 0.25 to 3.5 watts in 35 to 40 Kelvin range with Neon
 - Temperature can be controlled to any desired level within the operating range
- CCPL can be used in a cryogenic thermal bus or as a temperature control device
- CCPL flight experiment successfully flown on STS-95 in October 98
 - Demonstrated start-up and transport up to 2.5 W@ 80 to 100 Kelvin
 - Included breadboard superconductor bolometer from Code 690
 - Future development - Operation in the 2 to 4 Kelvin range with Helium

CCPL Flight Unit Design

CCPL-5

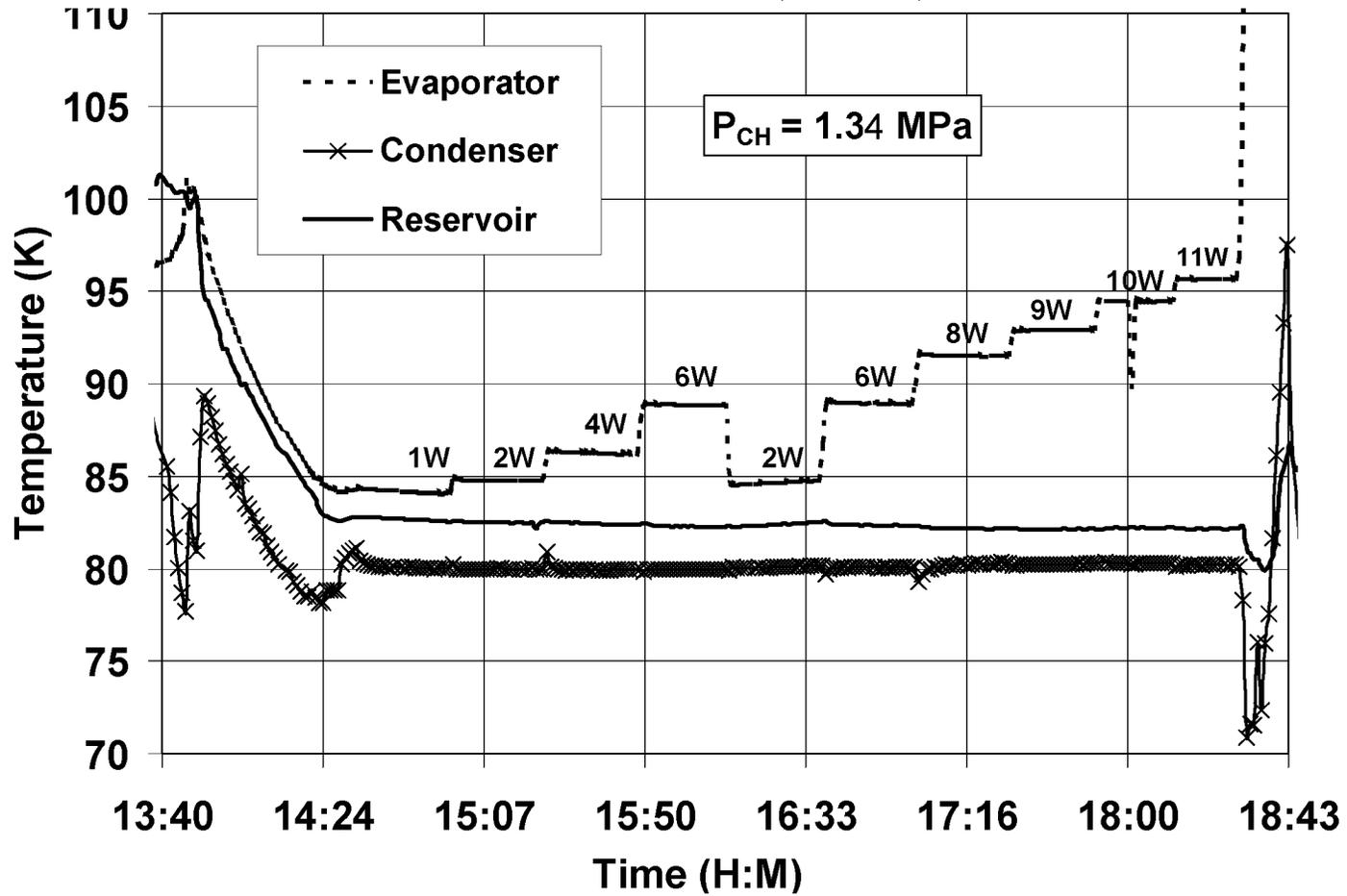


Neon CCPL



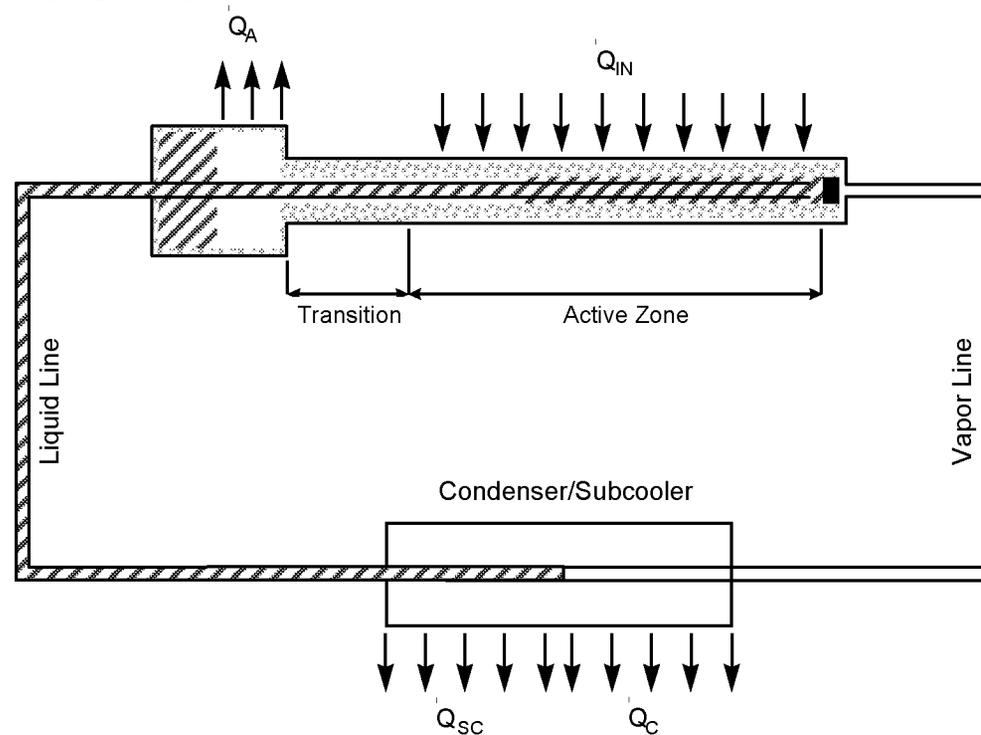
Ground Testing

CCPL-5 Results (Cont'd)



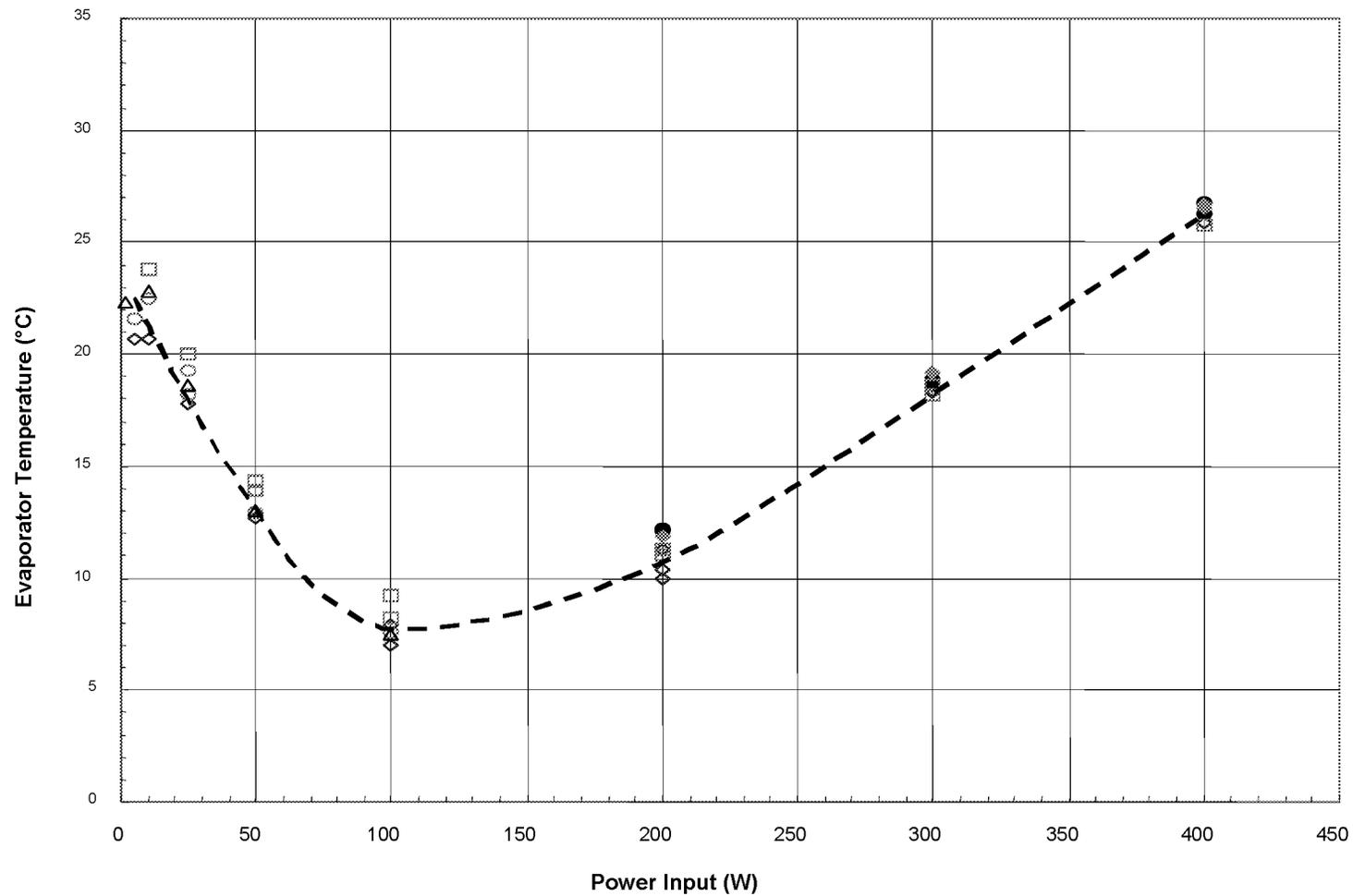
Loop Heat Pipes (LHP's)

- Description - LHP's are basically similar to CPL's - transfer large amounts of heat via the heat of vaporization of the working fluid, and can be shut down
- Invented in Russia in the 70's
- LHP's compensation chamber (reservoir) is attached directly to the evaporator, versus a remote location for CPL's



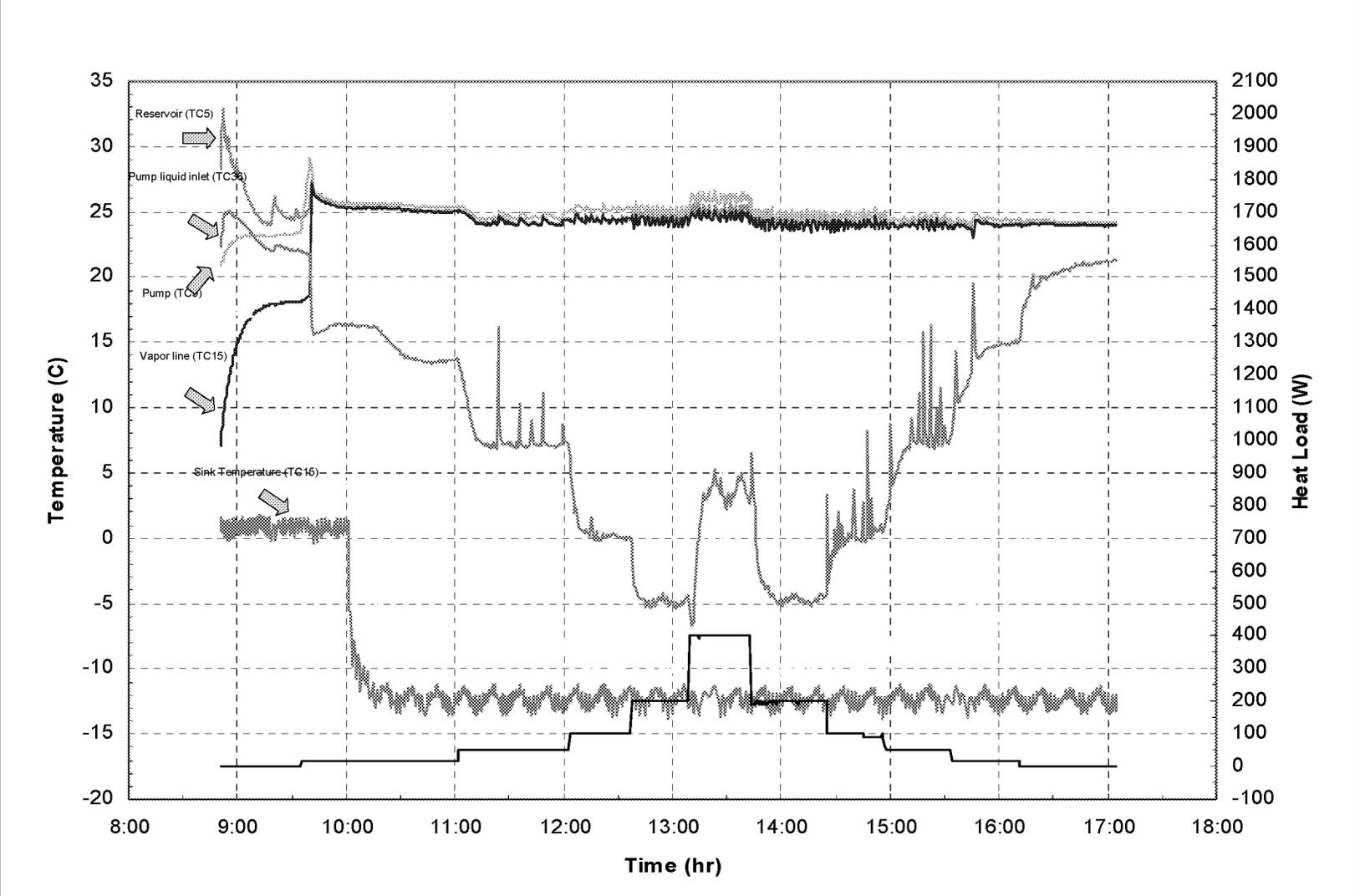
OPERATING TEMPERATURE

NO CONTROL OF COMPENSATION CHAMBER



OPERATING TEMPERATURE

ACTIVE CONTROL OF COMPENSATION CHAMBER

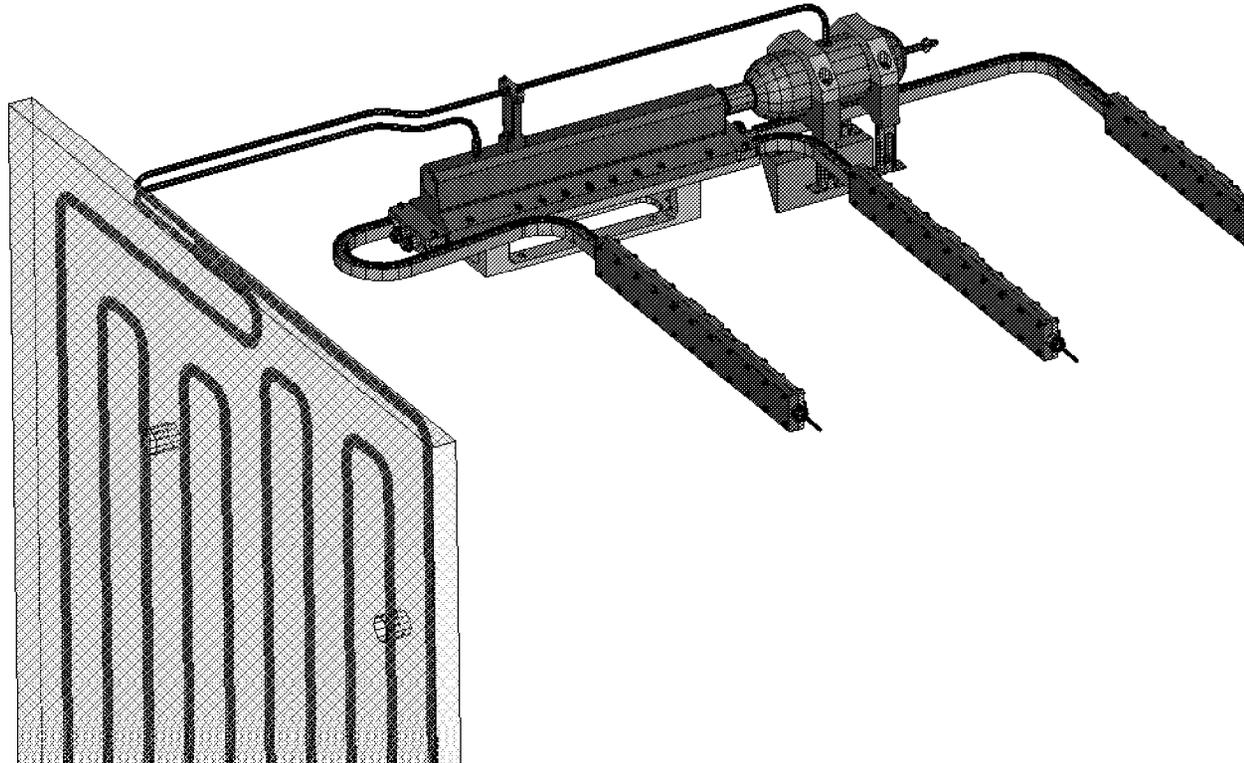


LHP Technology

- Both Swales and Dynatherm LHP designs were flown in 1997 shuttle experiments - Many Russian loops have also flown.
- Programs
 - GLAS Instrument (GSFC) - 2 LHP's for laser and electronics
 - EOS/AURA, TES instrument (JPL) - 5 LHP's for electronics, cryocooler
 - GOES/NEXT (Hughes) - 6 LHP's for star tracker, electronics
 - VASMIR (JSC) - high flux LHP for rocket cooling
 - M1 Tank (US Army) - electronics cooling, testing up to 5 G's
 - Nanosat & Mars Rover (JPL) - mini-LHP development
 - Baselined for the MARS 03 Rover mission
 - Swift BAT Instrument (GSFC)- 2 loops cool detector plate
 - Boeing/Hughes 702 satellites use LHP's with deployable radiators
 - Several on-orbit and operating
 - Mini-LHP development program

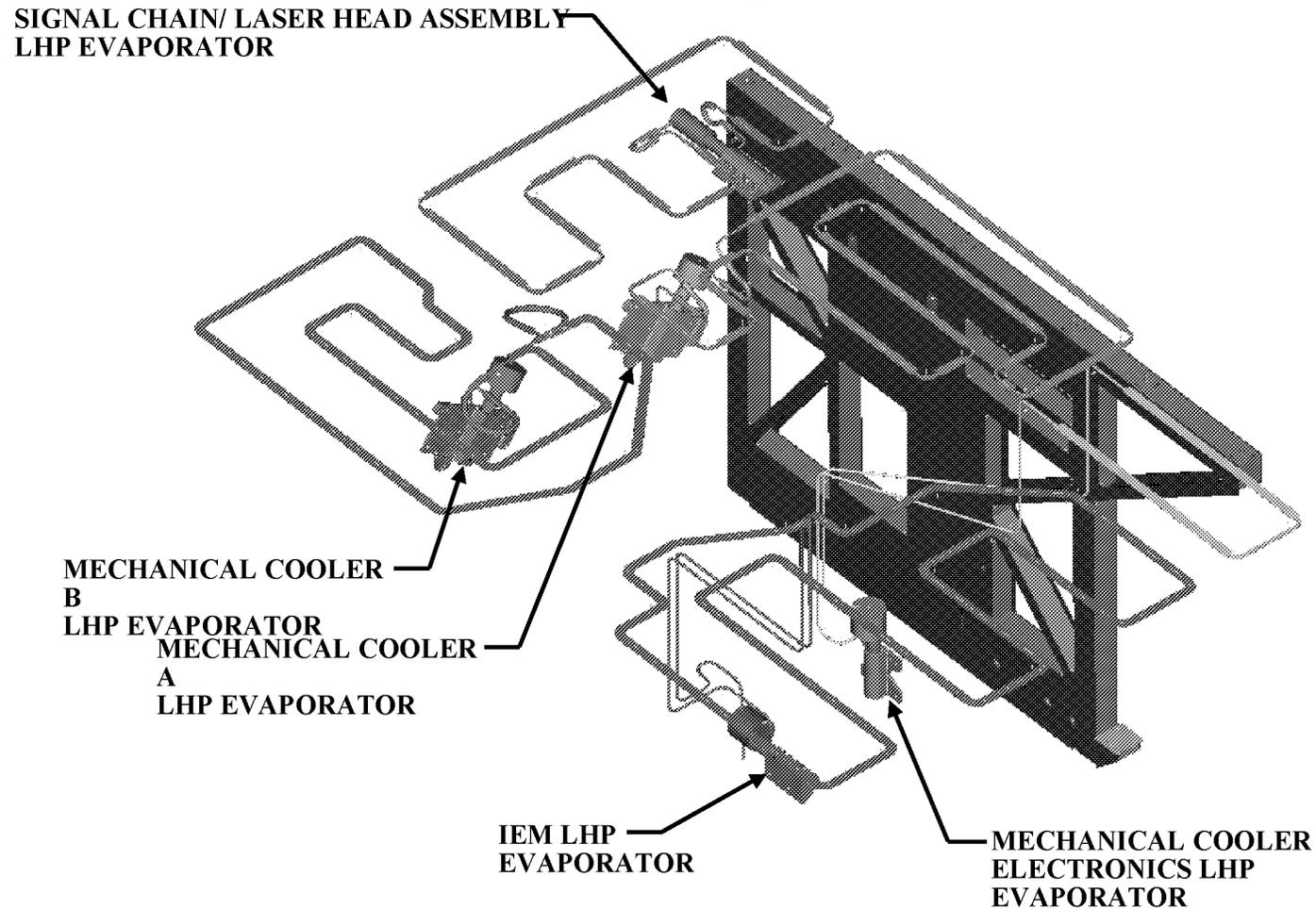


GLAS LOOP HEAT PIPE

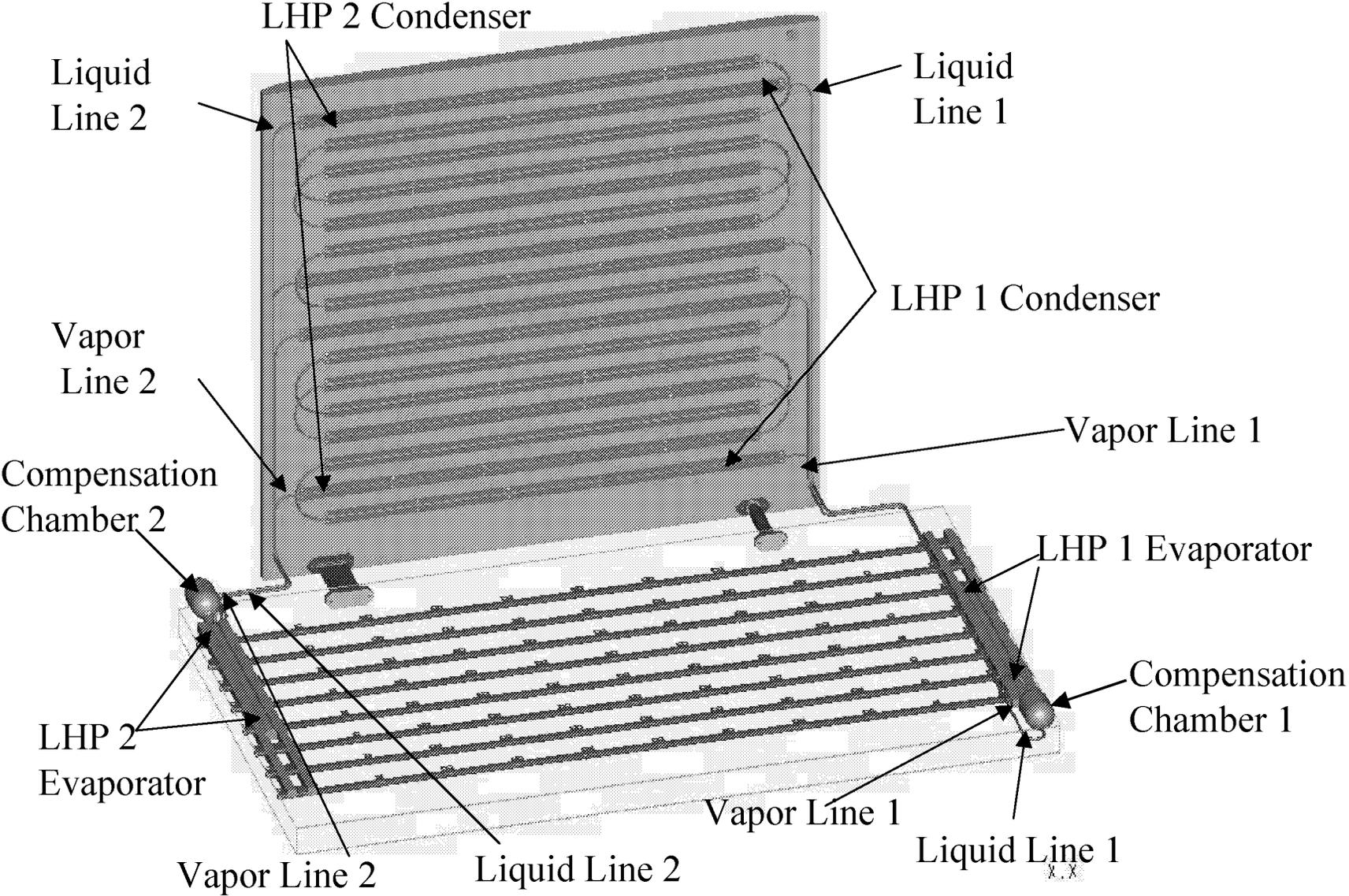


EOS-CHEM TES INSTRUMENT

Loop Heat Pipe Layout



SWIFT/BAT LHP



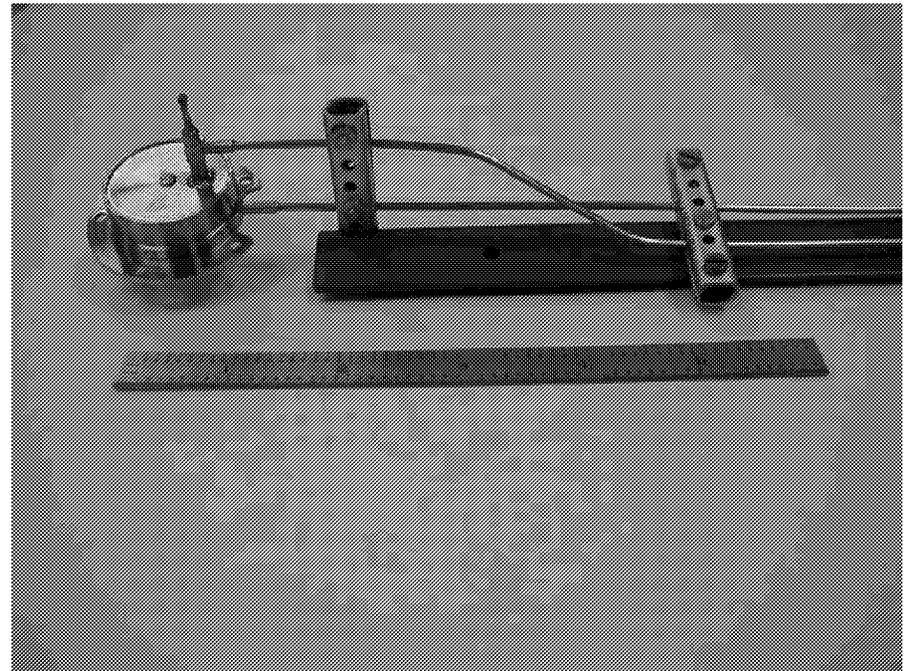
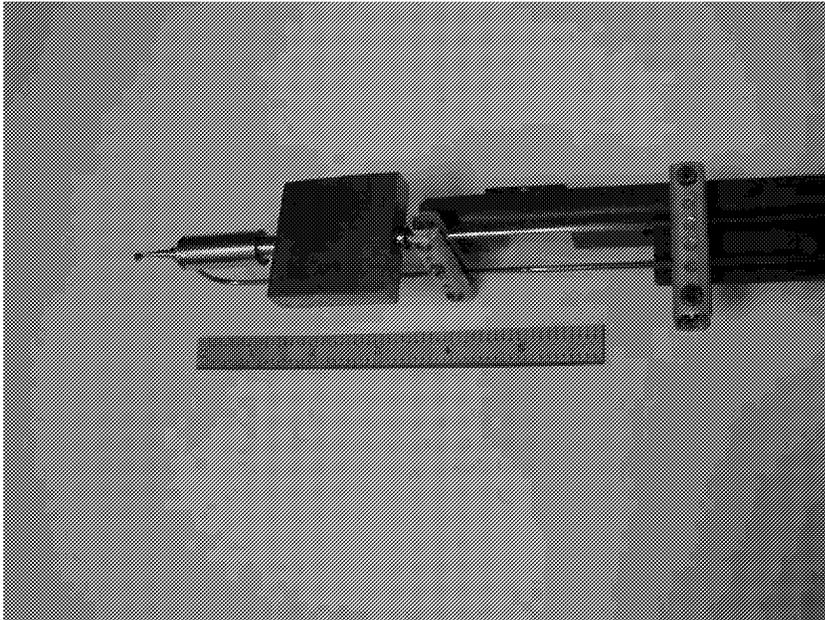
Mini-LHP

- **Miniaturization of existing technology**
 - currently have 1/2" dia evaporators
 - goal of 1/4" diameter evaporator
 - up to 10 of watt transport over < 1 meter length
- **Application to nanosats, electronics cooling**
 - allows isolation of spacecraft interior during cold case
 - especially suitable for fleets of S/C
- **Recent SBIR Phase 2 with TTH Research Inc./Thermacore**
- **HQ Award to GSFC (CETDP)**

Mini-Loop Heat Pipe



Russian mLHP's



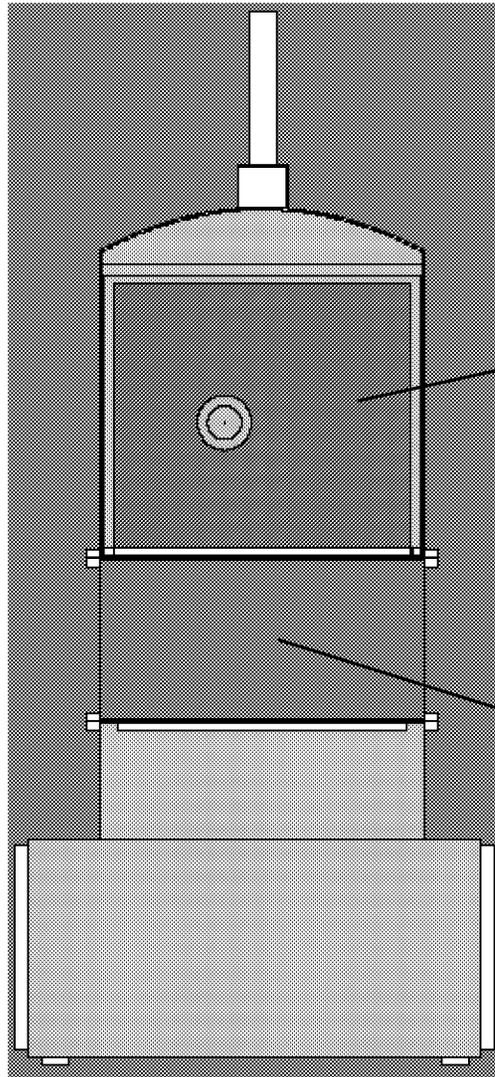
Mini-LHP Technology Issues

- mLHP performance does not scale linearly
 - Thermal coupling (heat leak) between compensation chamber and evaporator affects start-up capability and operating temperature
 - Previous experience on Capillary Pumped Loops shows that performance affected by size
- Manufacturing capabilities on a small scale
 - Wick fabrication and secondary wick installation
- Development of a high conductance condenser
- Thermal/Fluid dynamics on a small scale
- Gravitational affects on liquid/vapor fluid management

Heat Pumps

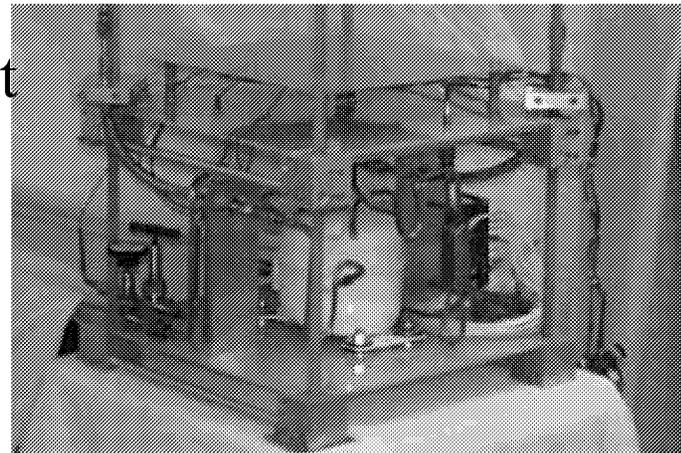
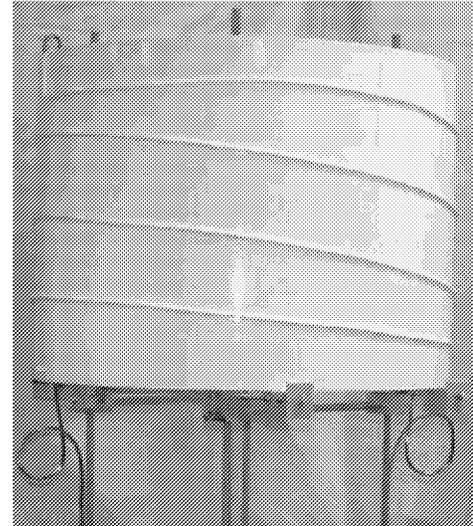
- Description - Heat pumps provide heat rejection at an elevated radiator temperature
 - Utilized in hot environments or to reduce radiator area (S/C real estate).
- Commercial units are unfit for vacuum and microgravity.
- Program in FY 99/00 - collaboration with the University of Maryland
 - Breadboard heat pump completed and tested in a vacuum environment
 - Upgrade of commercial unit for vacuum (approx 200 W)
 - Still need to address micro-gravity issues
 - Mini-heat pump development study (10 to 20 W) in FY 00
- Potential Applications - ULDB (balloon) thermal control in hot environments, ISS, Lunar Base, Hi-power Comsats, Laser cooling
- Penalty of weight and power

Heat Pump in Vacuum Test Chamber



Cold Sink
Environment

Gondola
Environment



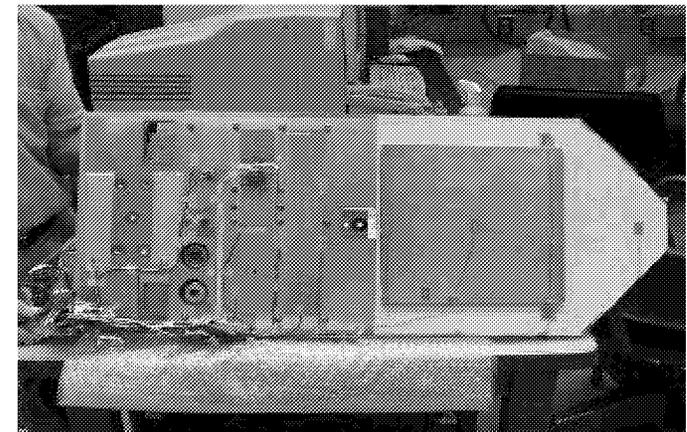
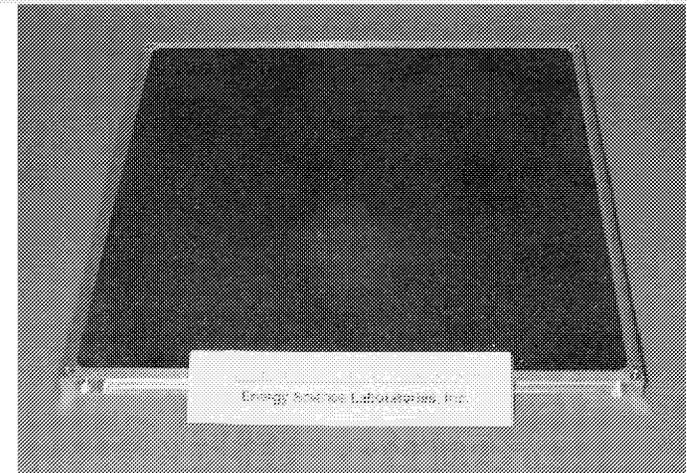
Phase Change Thermal Storage

VCL

Phase Change Module Design

*Vegetation
Canopy
Lidar*

- **Prototype Phase Change Module Procured and Tested**
- **Dimensions - 10 x 10 x 0.4 inches thick**
 - PCM (Hexadecane Mass) ⇒ 430 grams**
 - PCM Melting Point ⇒ 18.2 °C**
 - Total Latent Heat Capacity ⇒ 30 Watt Hours**
 - Total Mass Per Module ⇒ 650 gram**
- **Overall geometry provides high heat transfer from heat pipe radiator to phase change module**
- **All four heat pipes located beneath laser chassis and phase change module footprints.**
- **Phase change module consists of a core assembly and face sheets.**
- **The core assembly consists of a fine pore structure fabricated out of aluminum honeycomb with embedded high conductivity K1100 carbon fibers that provide high through thickness conductance and freeze nucleation sites.**
- **Prototype face sheets are bonded to the core with EpoTek T7109 adhesive.**



Variable Emittance Thermal Control Surfaces (VaryE)

- Variable emittance surfaces - Goal of 0.3 to 0.8 delta emissivity
 - Provides autonomous thermal control via a signal - “electronic louver”.
Three technologies in work - electrochromic, electrophoretic, and MEMS mini-louvers.
- Program - Baselined for thermal control demo on ST-5 mission ('04)
 - ST-5 funding from TRL Level 5 to flight
 - Air Force SBIR for electro-chromic (Ashwin-Uhas)
 - GSFC SBIR for electrophoretic (Sensortex)
 - CETDP for MEMS louver (APL/Sandia)
- Application/Payoff - Generic applicability to all S/C and instruments, large and small. Potentially very inexpensive as a solid state device

MEMS Louvers

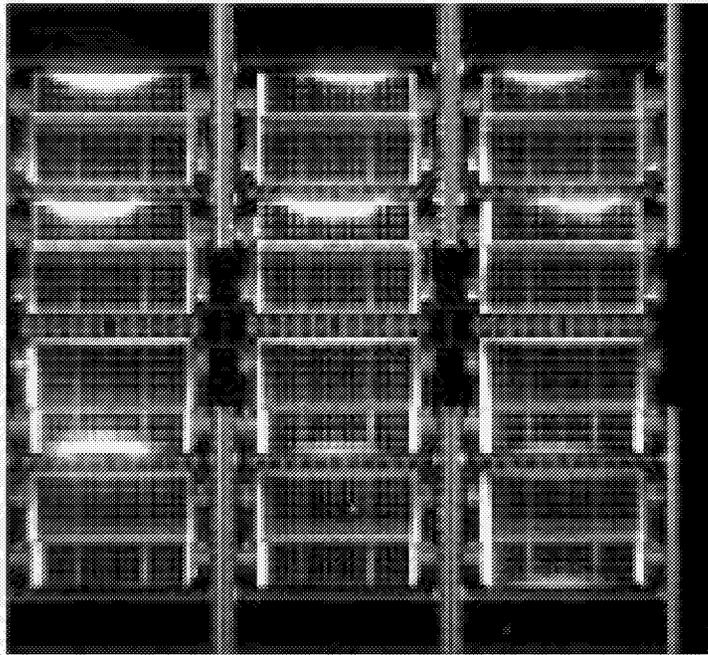


Figure 1 Louvers Closed

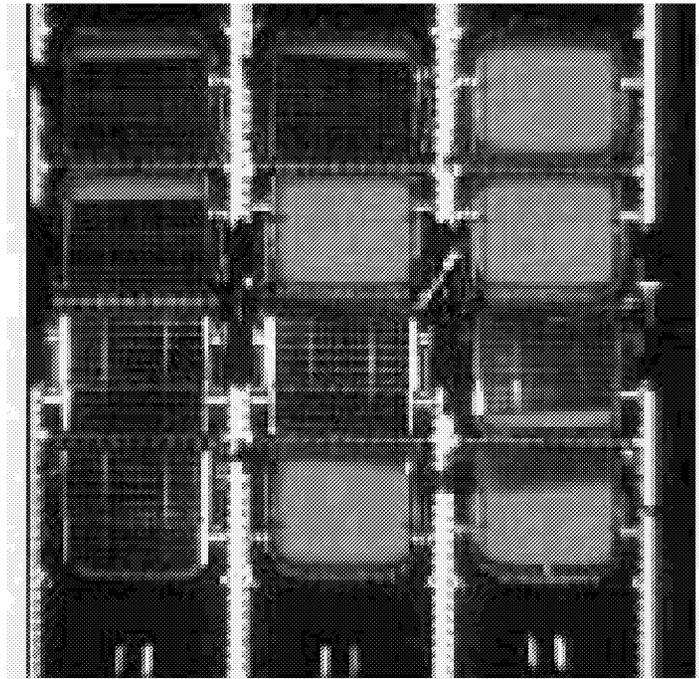


Figure 2 Louvers Open

Thermal Coatings Technology on the EO-1 S/C Launched in November 2000

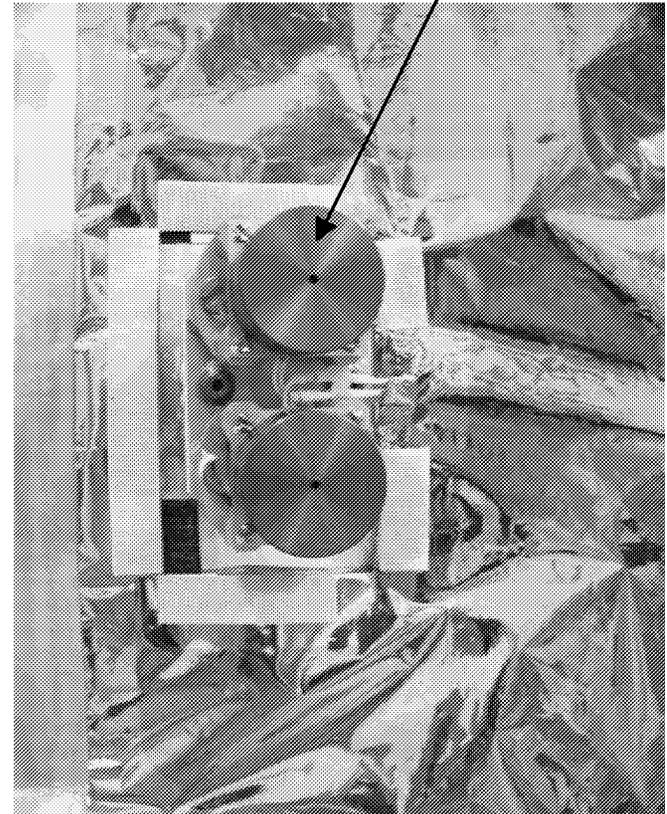
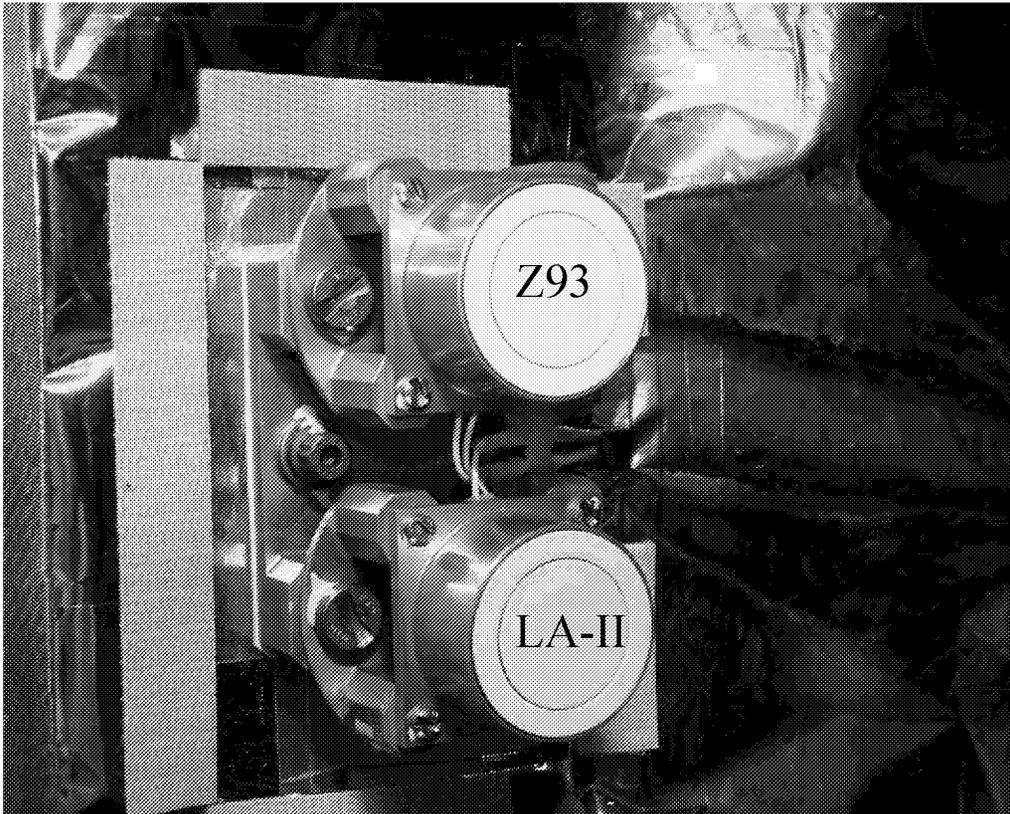
- Two Flight Thermal Coatings – White Paint
 - Z93P White Paint: Calorimeter (S/N 032) Current technology - control sample
 - AZW/LA-II low alpha inorganic White Paint: Calorimeter (S/N 033) New technology
 - Both coatings developed by AZ Technology
- Z93P White Paint (S/N 032)
 - $\alpha = .17, \epsilon_h = .87$
- AZW/LA-II White Paint (S/N 033)
 - $\alpha = .11, \epsilon_h = .86$
- Flown on calorimeters built at GSFC (reduce S/C thermal effects)

Calorimeters on EO-1

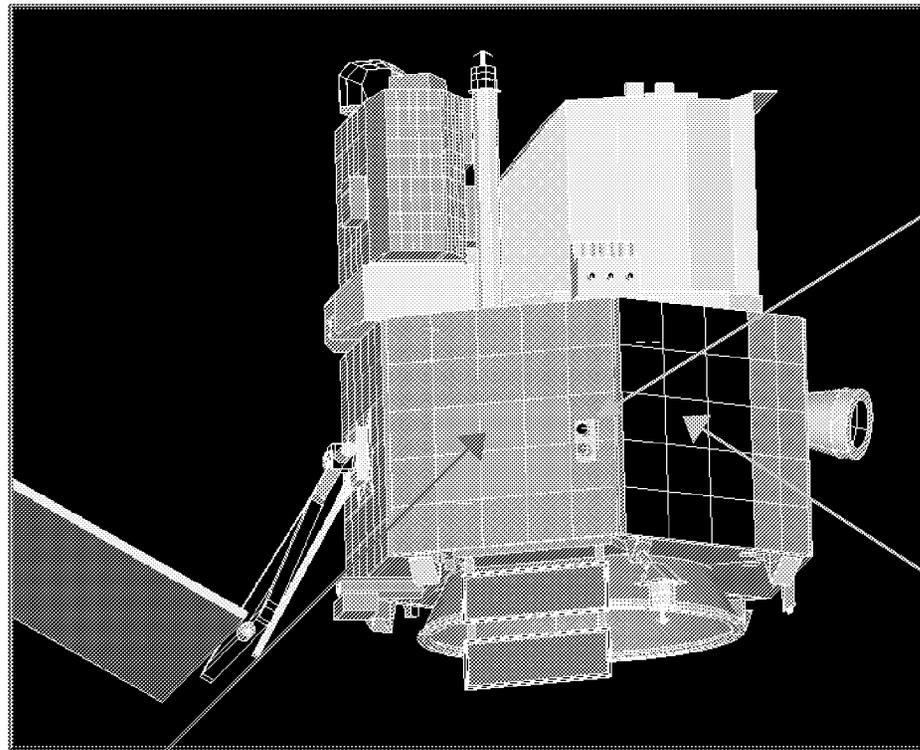
- The Calorimeters are mounted on a bracket and attached to the C-C radiator (Bay 4)
- The LA-II coating (“low alpha”) has a very low solar absorptance value when compared to other space application white paints.
 - A lower solar absorptance can provide improved radiator performance when exposed to UV. This improvement can lead to smaller radiator sizes, saving spacecraft mass.
- LA-II optical properties verified maintaining stability with improved solar absorptivity vs. Z93
- LA-II may provide cooler radiator temperatures when exposed to UV:
 - Data shows 5°C cooler in UV
- Baselined for the Swift Spacecraft (but it’s expensive)

EO-1 Calorimeters

Protective Covers



TSS Geometric Math Model

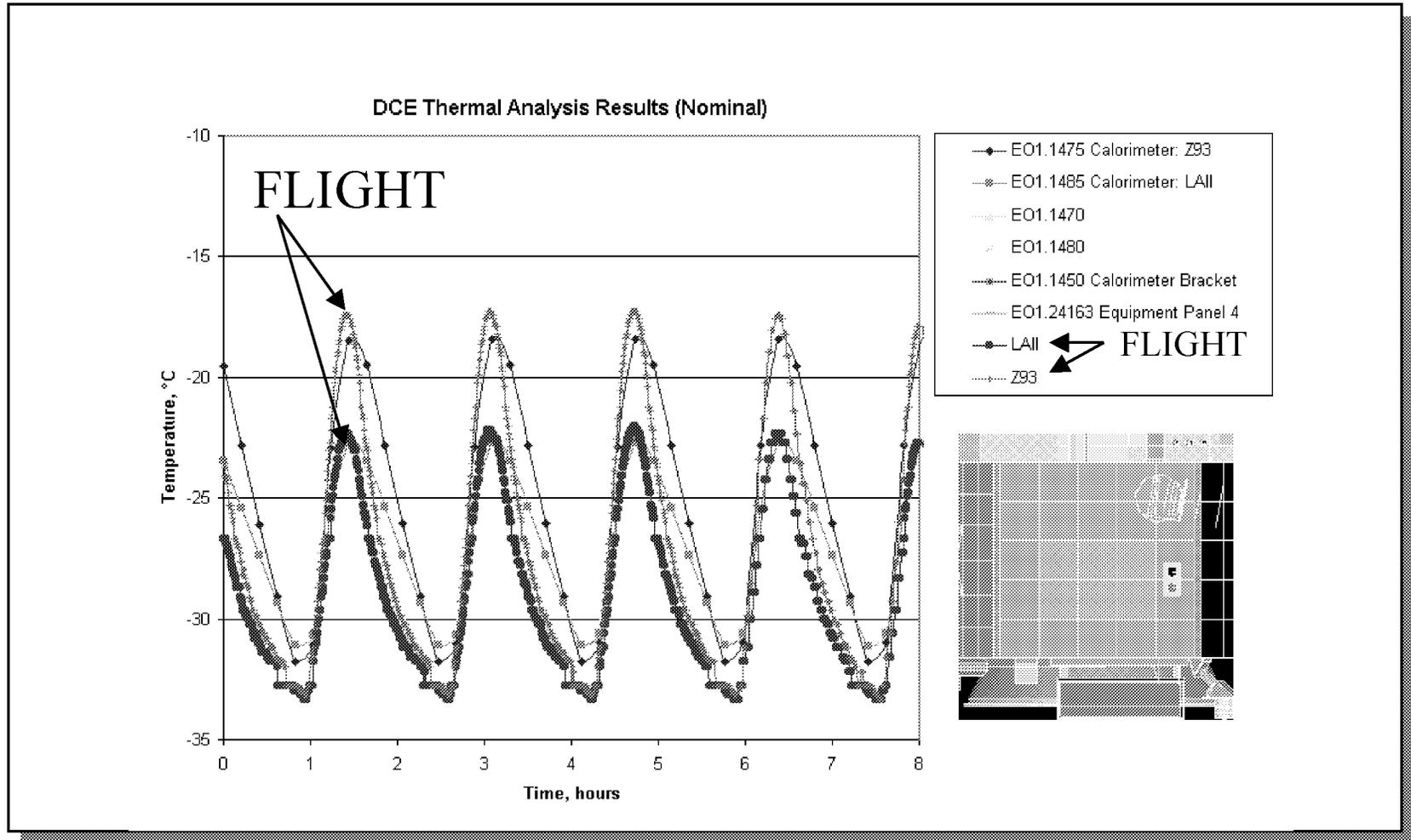


Calorimeters

Louver

Bay 4 Radiator

Transient Flight Data vs. Thermal Model Analysis



High Conductivity Materials

- Lightweight electronics box (K1100) - IRAD exercise
- Incorporated K1100 composite panels as electrical box mounting panels/radiators on WIRE (1999)
- MAP - gamma alumina at low temperatures (2001)
- Carbon-Carbon radiator on EO-1 (2000)
- Diamond Material for electronics cooling
- SBIR's with Ktech for Annealed Pyrolytic Graphite (APG)
 - Thermal Straps
 - Cryogenic Radiators for possible NGST application

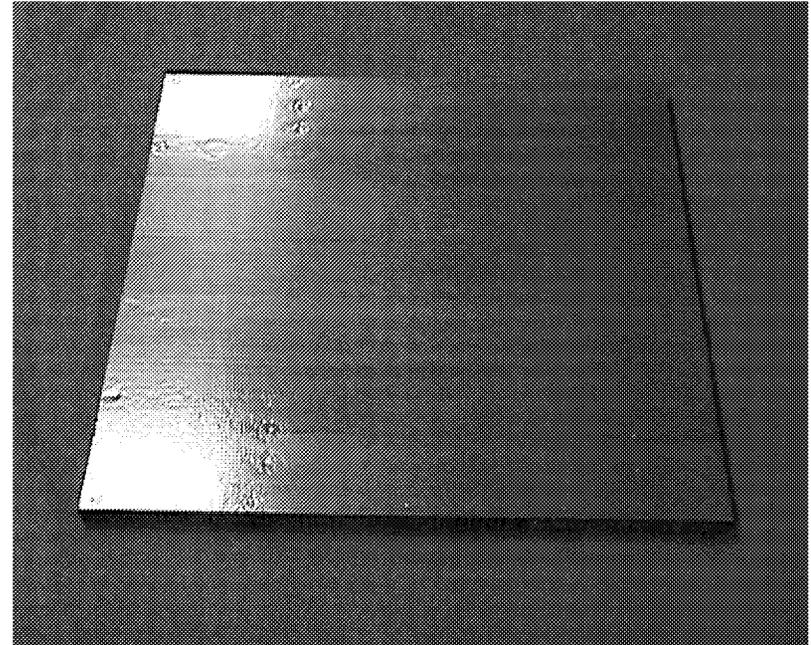
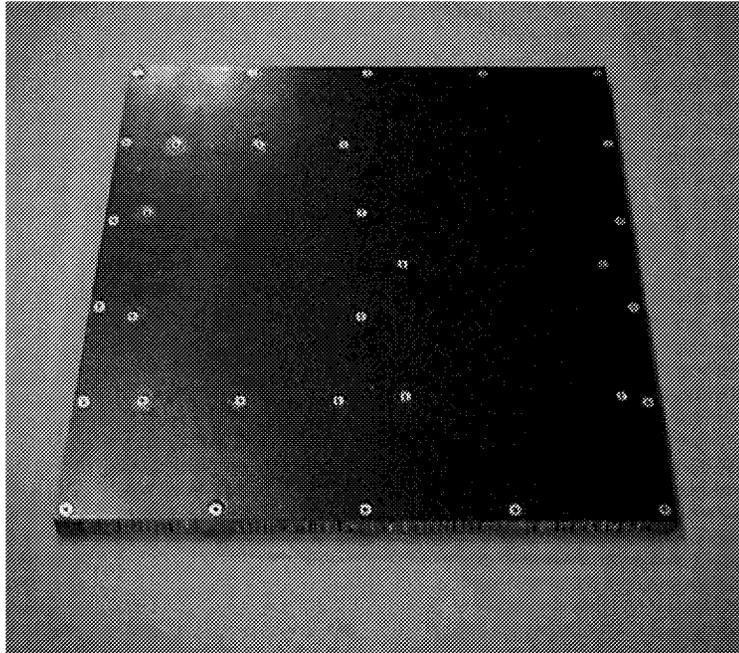
Carbon-Carbon

- Carbon-Carbon (C-C) - Composite material that uses carbon for both the fiber and the matrix material
 - produced in a high temperature furnace in a lengthy process
- C-C has high thermal conductivity, good strength, and is lighter than Aluminum
 - C-C used in high temperature applications such as aircraft brakes, Space Shuttle wing leading edge
- Limited applications elsewhere to date, primarily due to cost and production lead time
- Carbon-Carbon Spacecraft Radiator Partnership (CSRP) formed to promote the use of Carbon-Carbon as a radiator material
 - informal partnership with members from government and industry

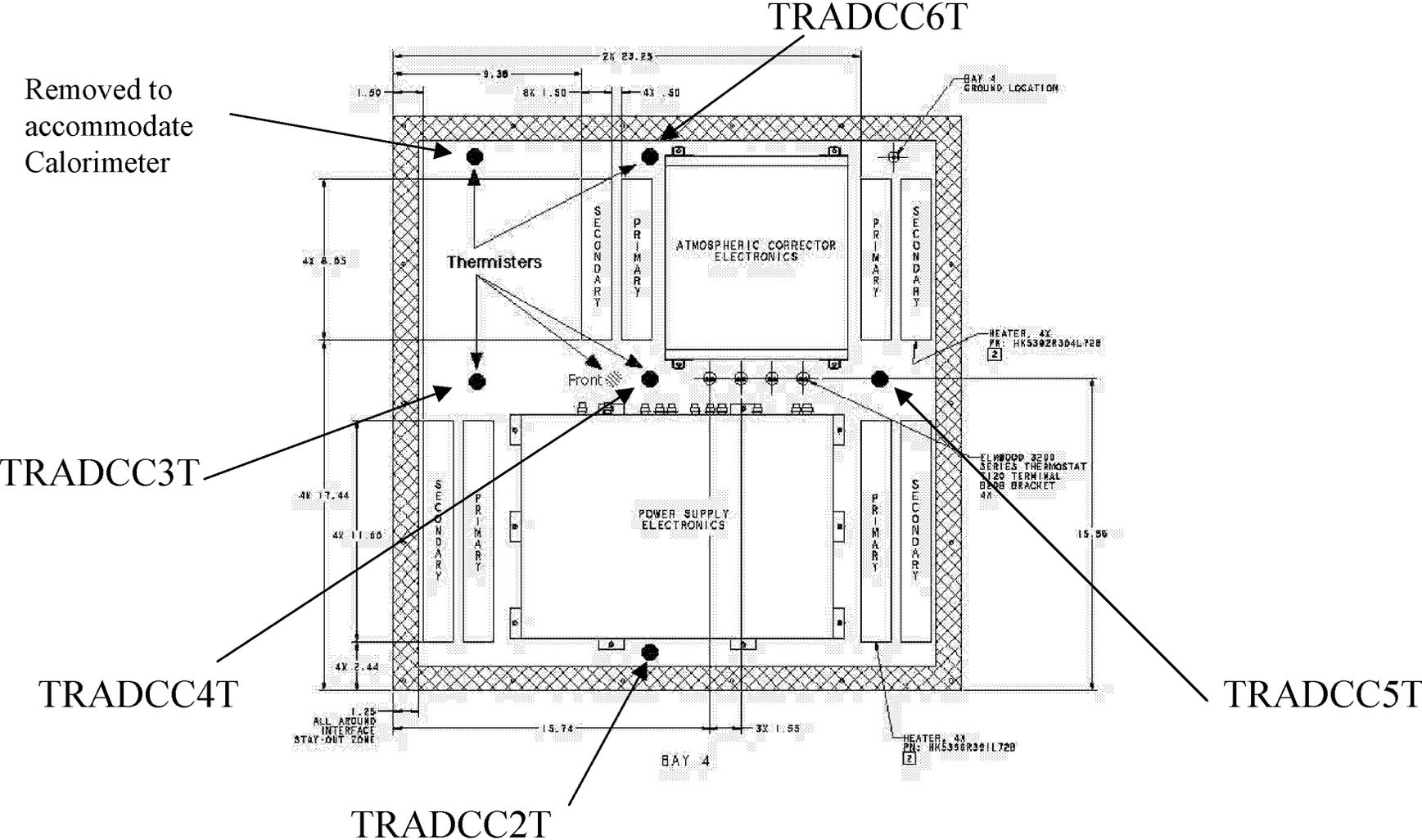
C-C Radiator on EO-1

- The New Millennium Program's EO-1 mission provided an opportunity for the CSRP to fly a C-C radiator
 - C-C radiator provided by CSRP at “no cost” to NMP
- The C-C radiator replaced one of 6 structural panels on the EO-1 Spacecraft - It is both a radiator and a structural member
- C-C Radiator consists of 1” Al honeycomb with 0.020” C-C face-sheets, approximately 28” by 28”
 - Utilizes 2 plies of P30X carbon fibers with carbon matrix established by Chemical Vapor Infiltration
 - Epoxy coated for strength and contamination protection
 - Aluminum inserts bonded to honeycomb core for mounting of electronics boxes and attachment to the S/C
 - Exterior coated with Silver Teflon for heat rejection
 - Flight qualification testing completed at GSFC

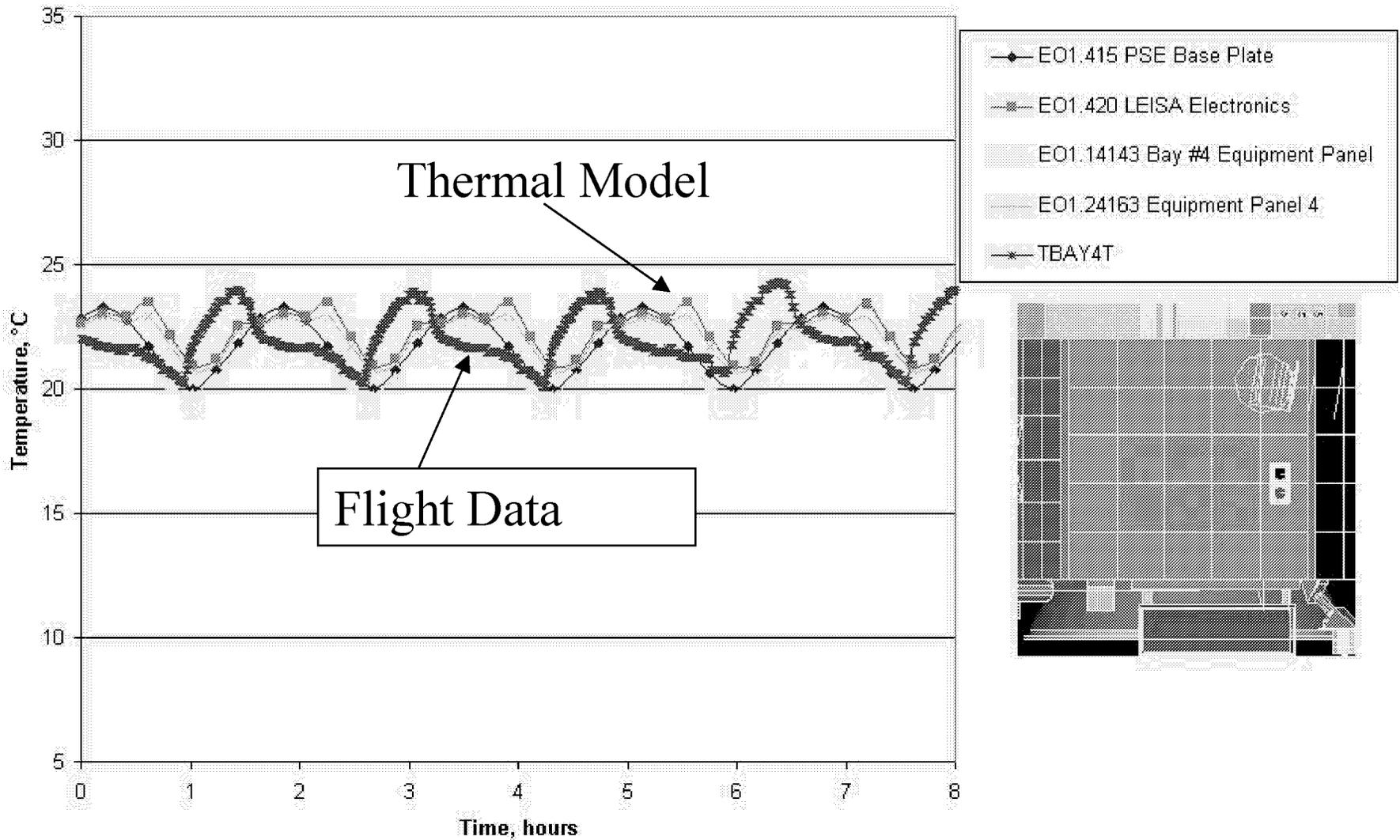
EO-1 C-C RADIATOR



CC Radiator Thermistor Layout



EO-1 DCE (Nominal) Thermal Analysis Results (December 2, 2000)



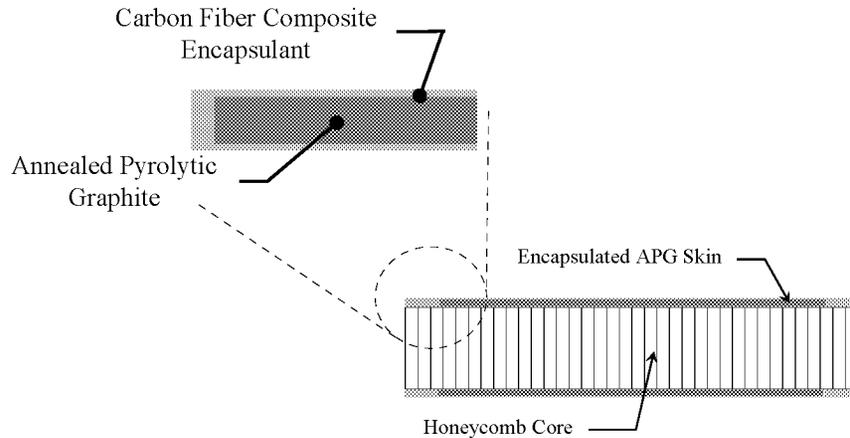
C-C Radiator Lessons Learned

- C-C Radiator technology was successfully validated
 - C-C radiator panels can be used to reduce S/C weight
 - They can also be used as part of the S/C structure
- C-C has a niche, especially for high temperatures
 - Application on the Solar probe
- C-C still needs further development (my opinion)
 - Reduction in fabrication time and cost - high conductivity “traditional” composites are competitive
 - CTE Interface issues with heat pipes
- Redundancy a good idea - we flew the spare panel
- Possible follow-on missions: C-C foam for low CTE mirrors/optical benches

CVD Diamond as a Heat Spreader

- Diamond is a unique substance.
 - Hardest known material
 - High thermal conductivity
 - Excellent mechanical strength
 - Electrical isolator, and may be used as a semiconductor.
- Recently received funding from HST to evaluate sample application as diode heat spreader
- Testing of Hi-K Diamond Underway (Norton Diamond)
 - TV testing for conductivity measurements completed - conductivity approx. 1000 W/mK
 - Vibration test in sample application in work (HST relay cooling)

Encapsulated APG Material System

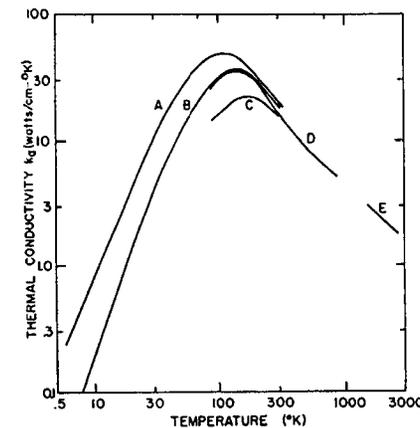


- ◆ Skin thermal conductivity
 - 1300 W/mK (273 K)
 - 2500 W/mK (120 K)
- ◆ Density less than 2.0 g/cm³
- ◆ Stiffness and strength equivalent to baseline designs

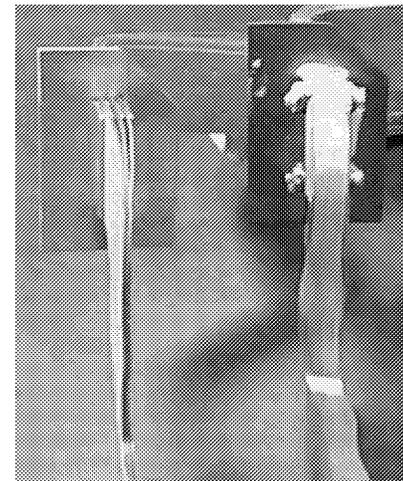
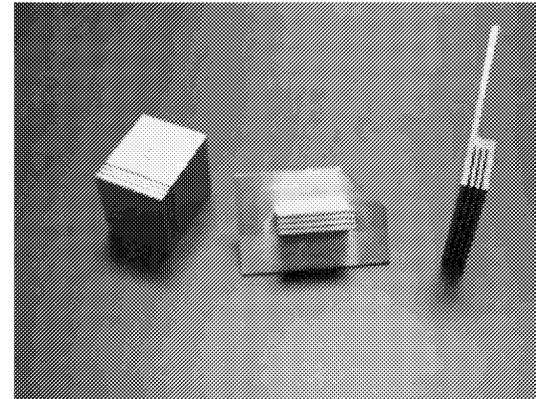
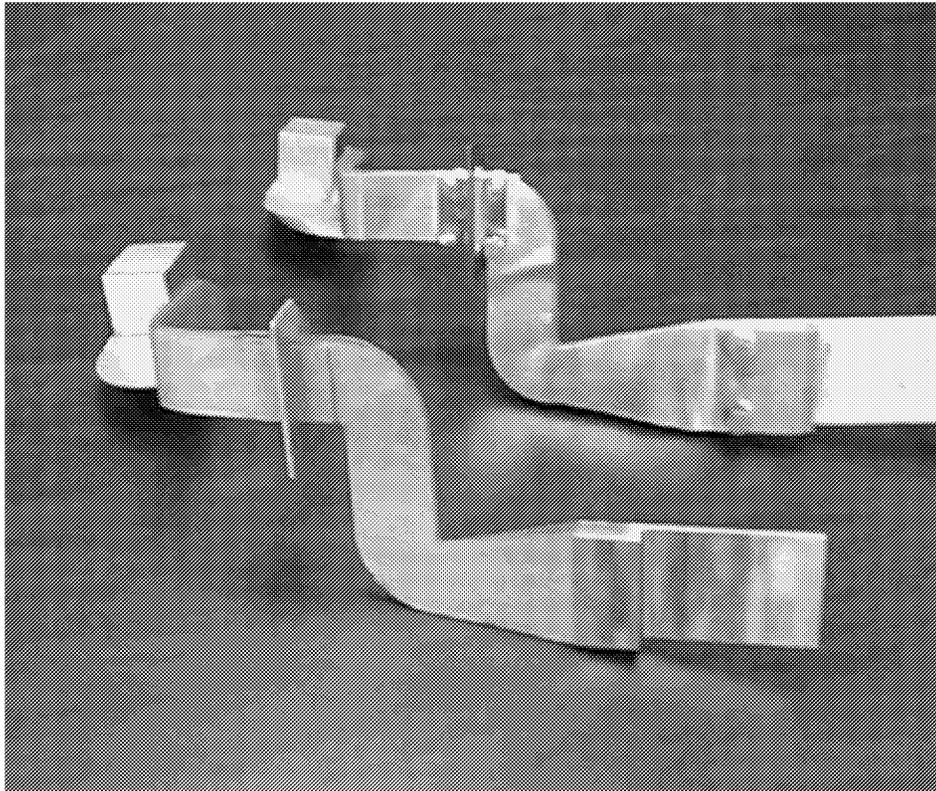
APG Properties

Property	Room Temperature (25°C)	Cryogenic (100°K)
Thermal Conductivity	1700 W/mK (a & b - Axis) 10 W/mK (c - Axis)	3400 W/mK (a & b - Axis) 50 W/mK (c - Axis)
Mass Density	2.26 g/cc	2.26 g/cc
Coefficient of Thermal Expansion	-1.0 ppm/K (a & b - Axis) 25.0 ppm/K (c - Axis)	-1.0 ppm/K (a & b - Axis) 25.0 ppm/K (c - Axis)
Thermal Diffusivity	9.8 cm ² /s	-
Specific Heat	0.84 kJ/kgK	-
Tensile Strength	1,000 ksi (a & b - Axis) 0 Ksi (c - Axis)	1,100 ksi (a & b - Axis) 0 Ksi (c - Axis)

Basal plane thermal conductivity of APG



Flexible Thermal Strap Fabrication



Thermal Strap Performance

Mass Comparison

	Mass	Reduction %
APG	218.00	58%
Aluminum	518.00	

Thermal Performance Comparison

	Power	Resistance (K/w)	Conductance (w/K)
Aluminum	20.68	3.16	0.32
APG	21.04	2.96	0.34

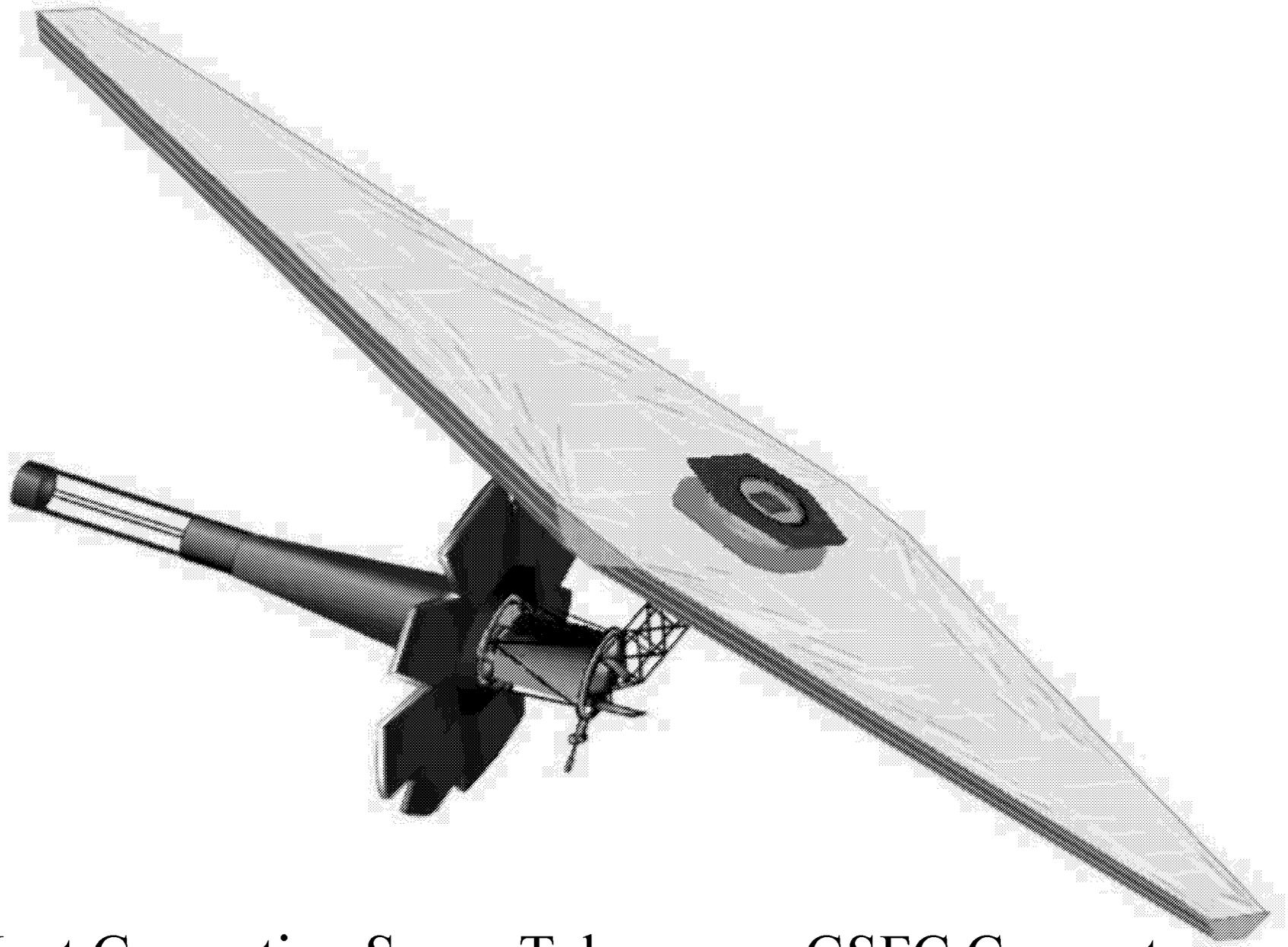
Thermal Outgassing Properties

	% TML *	% CVCM **	% WVR ***	Limits (%)
APG/Foil	0.024	0.010	0.020	1.000
Supreme 10ANHT	0.770	0.060	0.100	0.100

* Total Mass Loss

** Collected Volatile Condensable Materials

*** Water Vapor Regain

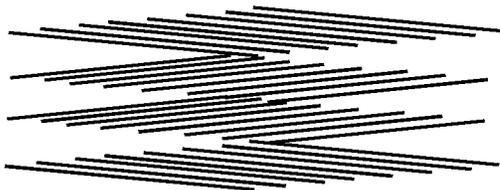


Next Generation Space Telescope - GSFC Concept

Fabrication of Radiator Panels

Phase I Results

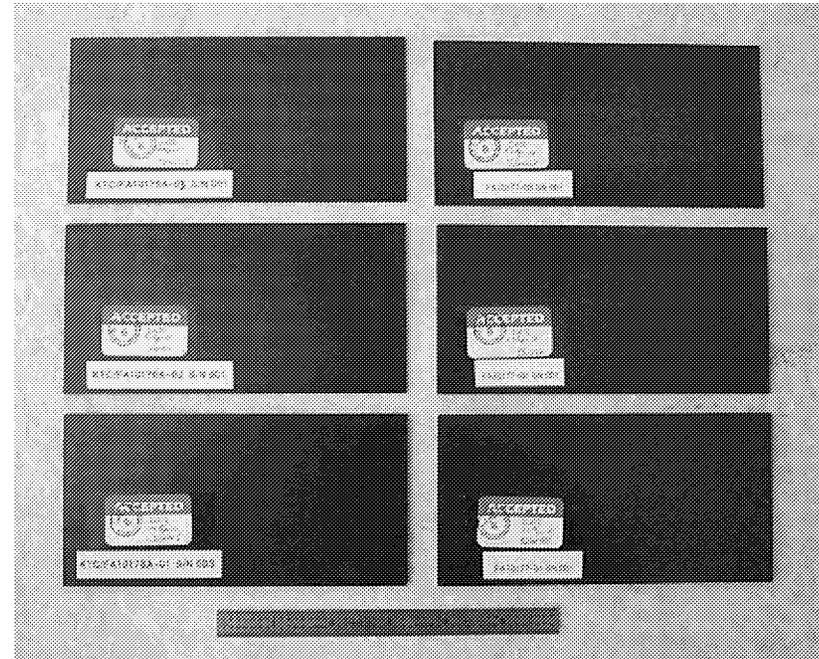
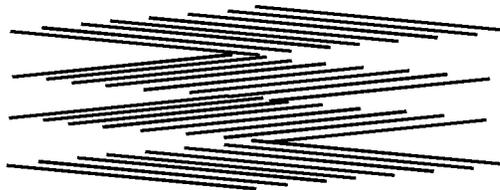
K13C2U/RS-3
[0/90/90/0]



APG Inset



K13C2U/RS-3
[0/90/90/0]



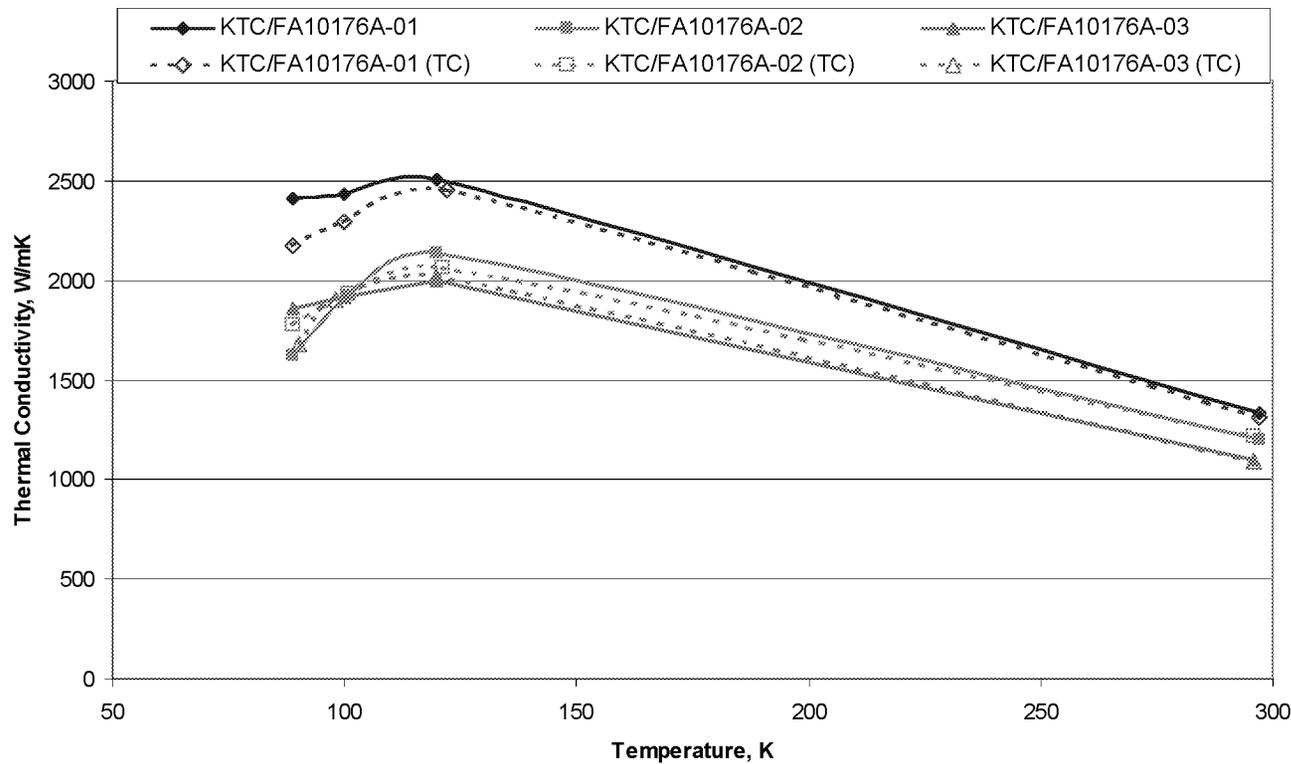
Part Number	Panel Thickness Nominal/Measured (inch)	Panel Width (inch)	Panel Length (inch)
KTC/IN10176A-01	.088/.092	2.999	5.999
KTC/IN10176A-02	.064/.068	3.001	6.000
KTC/IN10176A-03	.048/.050	3.001	6.000
KTC/IN10177-01	.088/.093	3.001	6.000

Panel Evaluation -- Measured Properties

Phase I Results

Conductivity -- Cryogenic Temperatures

Thermal Conductivity Vs. Temperature
Before and After Thermal Cycling (TC)



Max Average Values

Item	Measured k (W/mK)
IN10176A-01	2504
IN10176A-02	2134
IN10176A-03	1998

Electrohydrodynamic Pumping (EHD)

- Description - EHD forces can be used to enhance heat transfer, provide fluid management, separate gas/liquid mixtures, and pump fluids. Utilizes electrical forces only, with no mechanical moving parts.
- Working fluids - Dielectric refrigerant such as freon 134a, hydrocarbon, or nitrogen (cryogenic)
- Program includes partnerships with the University of Maryland and Texas A & M
 - EHD flow management test bed
 - EHD single phase and two-phase thermal control loops
 - Cryogenic EHD pumping test (LN2)
 - MEMS level cooling
- Application - Heat exchangers, ISS environmental systems, thermal control systems, MEMS level micro-channel cooling of electronics

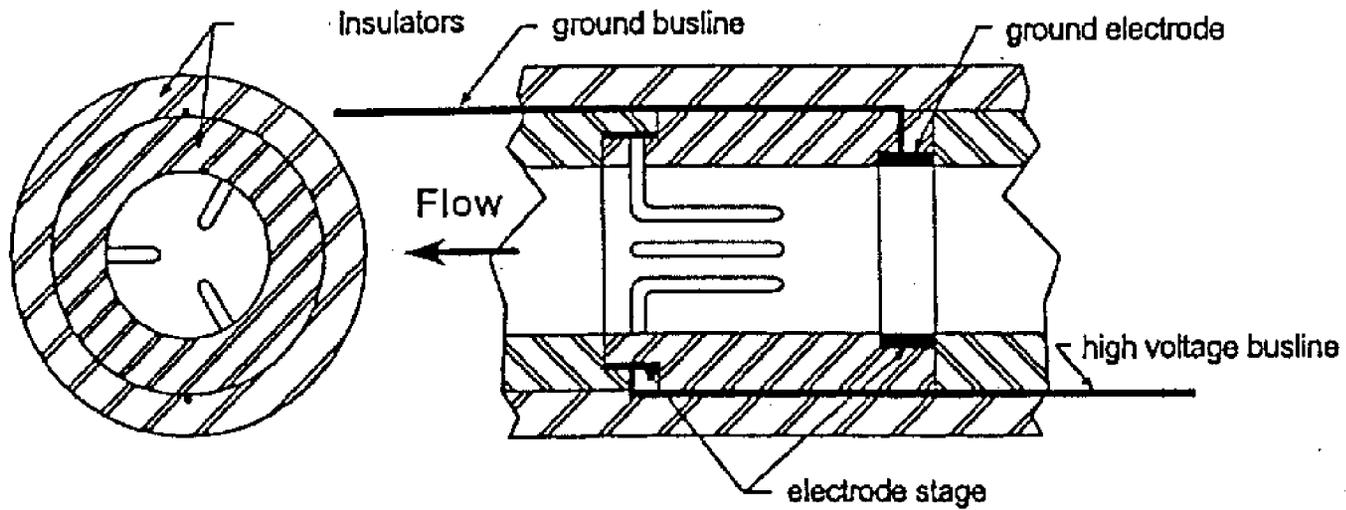
EHD PHENOMENA

- Electrohydrodynamics (EHD) is an interdisciplinary phenomena dealing with the interactions between electric fields and flow fields

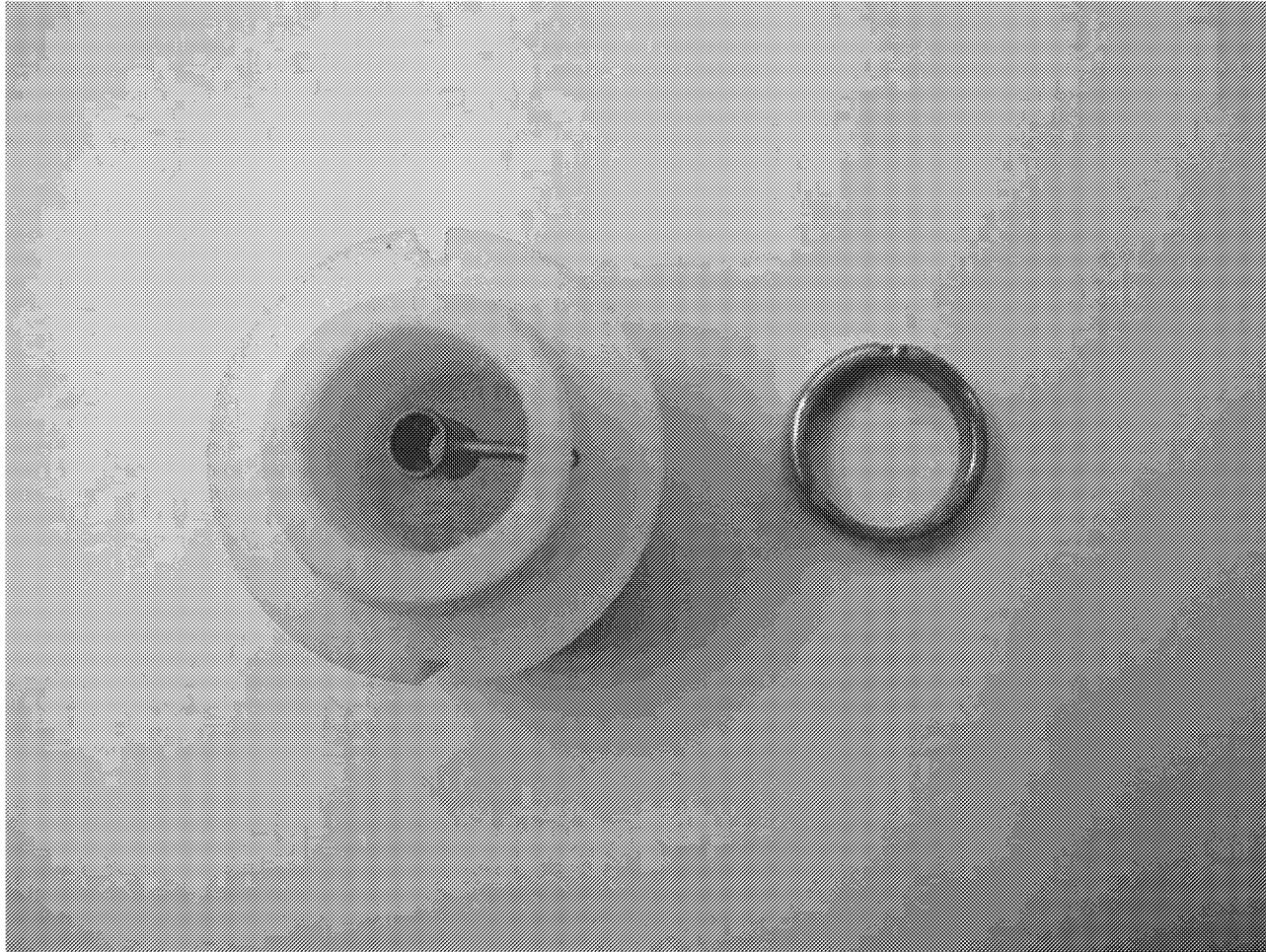
$$\bar{f}_e = q\bar{E} - \frac{1}{2}E^2\nabla\varepsilon + \frac{1}{2}\nabla\left[E^2\left(\frac{\partial\varepsilon}{\partial\rho}\right)\rho\right]$$

Coulomb Force Permittivity Gradient Force Polarization Force

EHD PUMP DESIGN

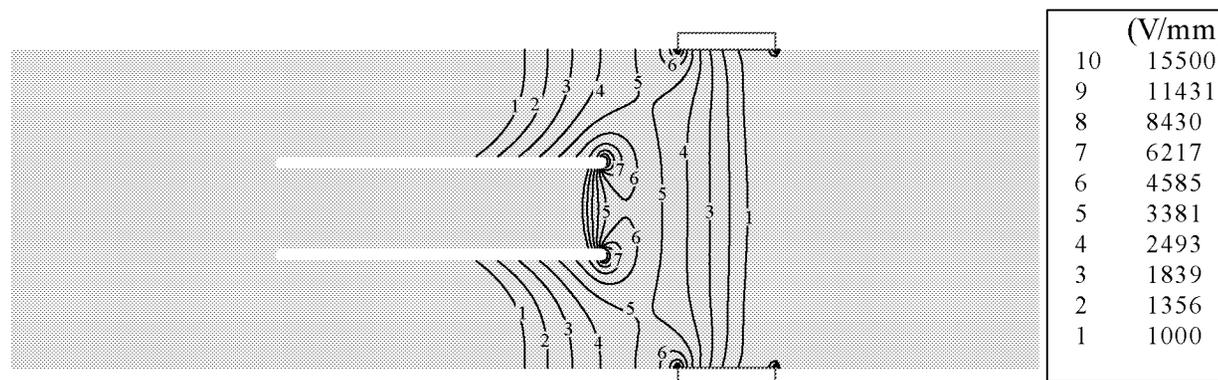


HOLLOW TUBE - RING ELECTRODE DESIGN

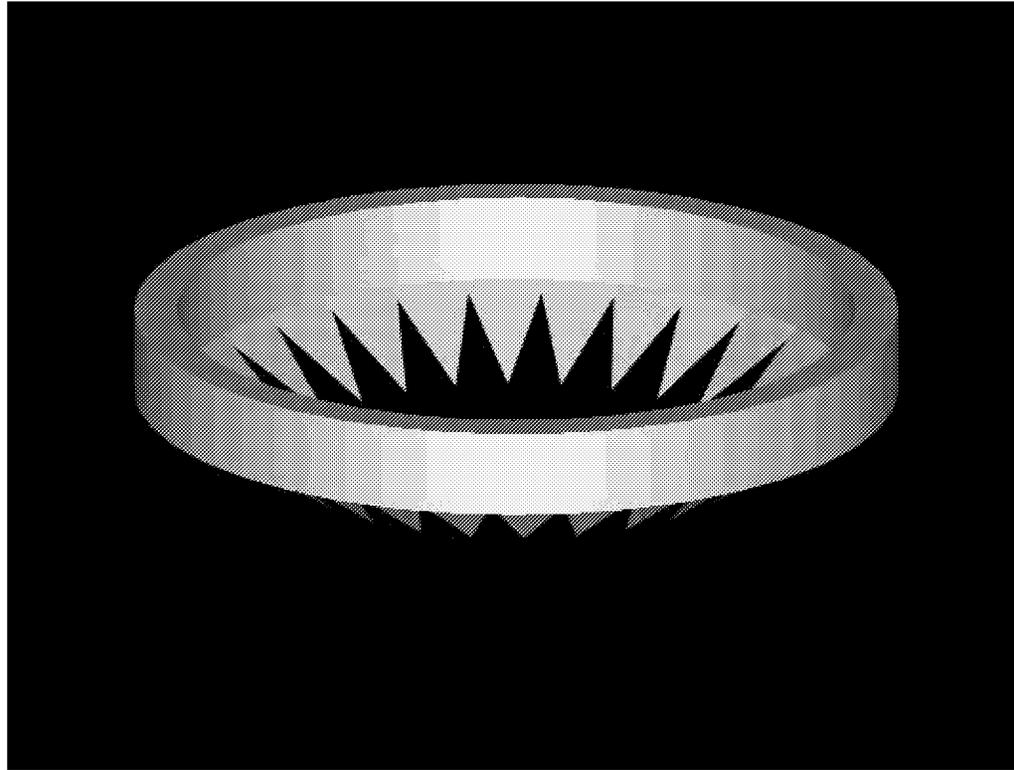




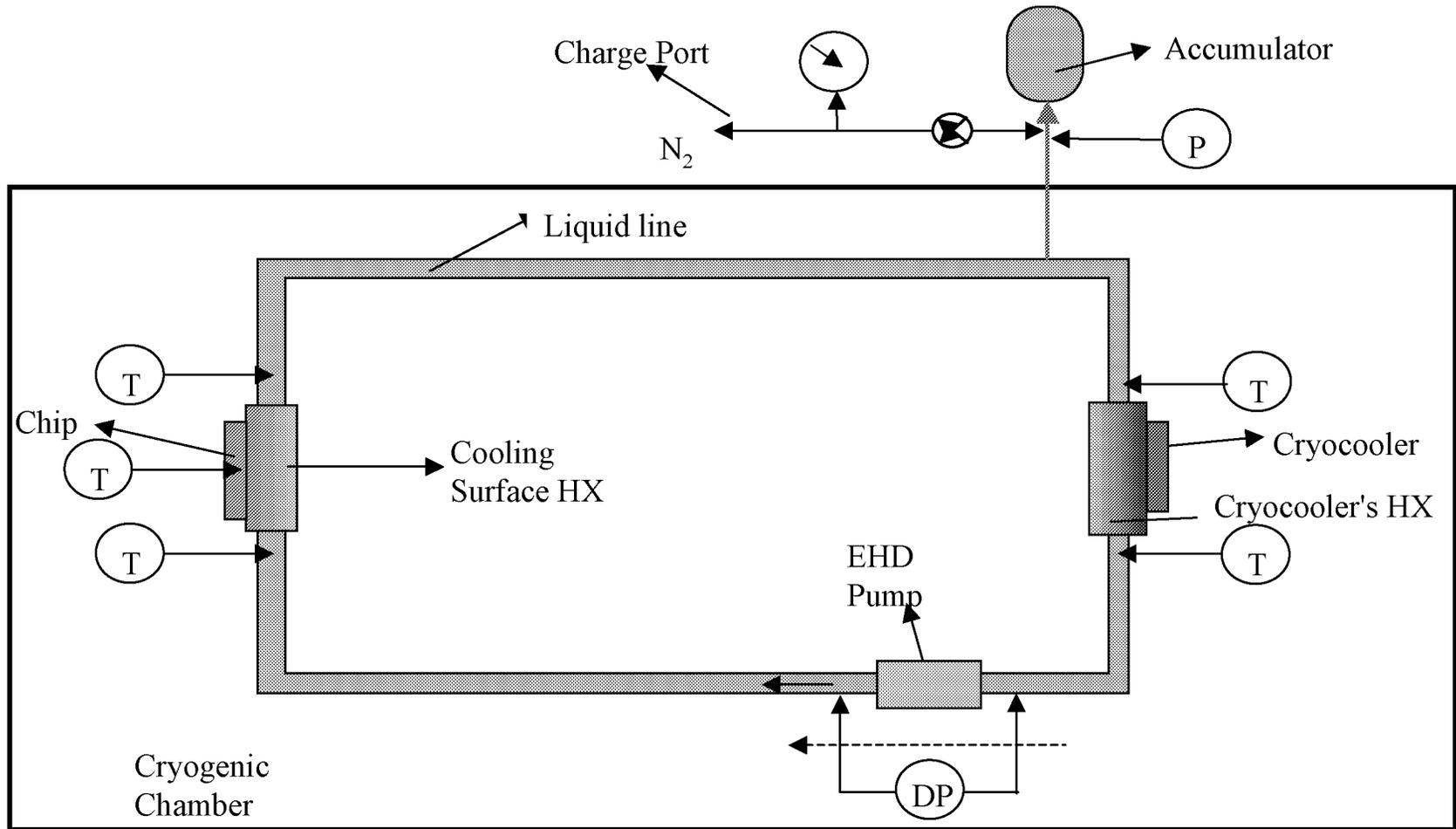
Electric Field



EHD Pump Design



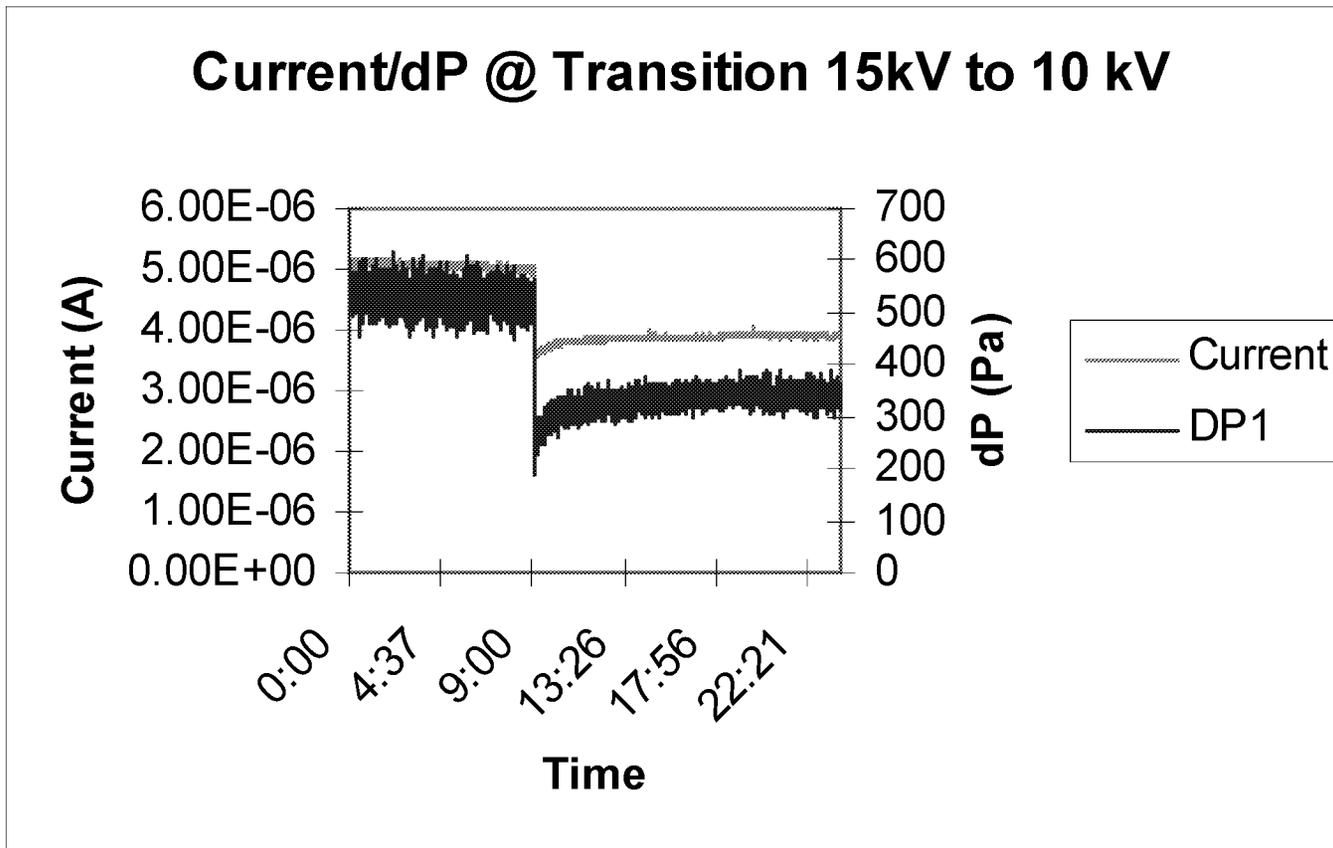
EHD Cryo/Loop Design



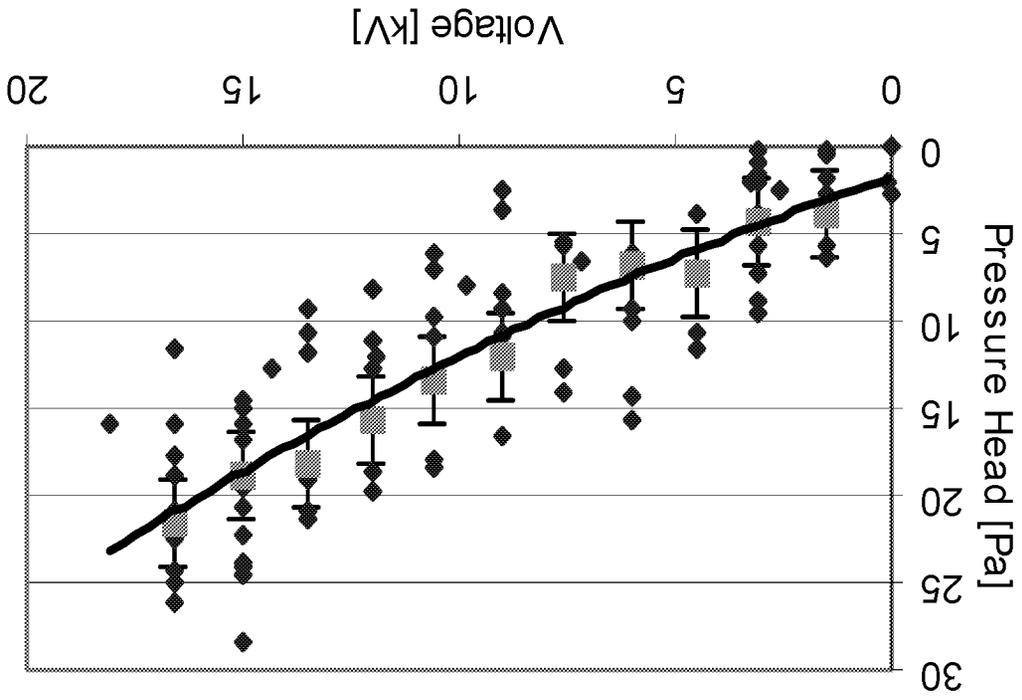
Prototype EHD Ambient Temperature Loop



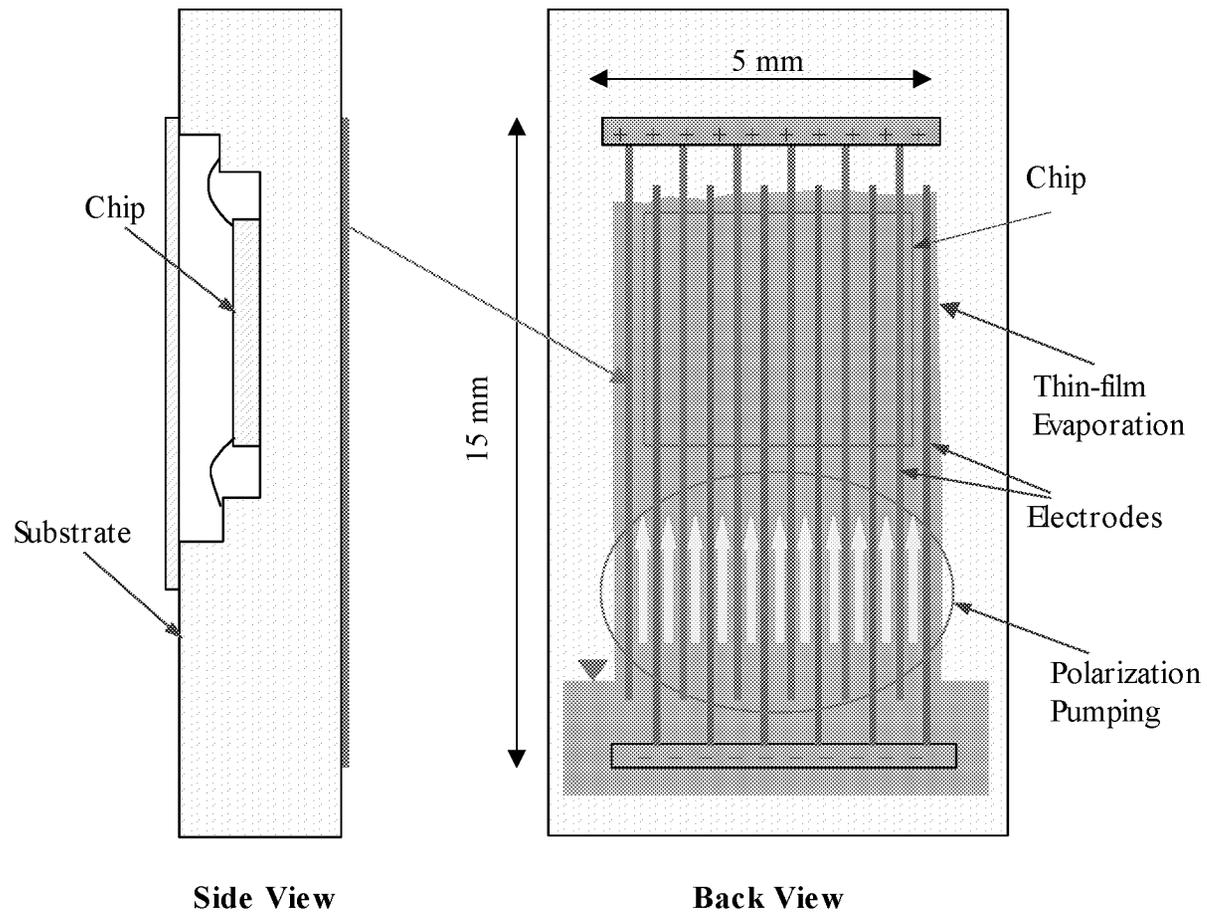
Conduction Pump Performance Ambient Temperature Loop



Cryogenic - Loop Pump Results with LN₂



EHD MEMS Cooling Concept



Future Technology Needs

- Dimensional stability of very large structures
- Diode action to minimize heater requirements
- Higher heat flux
 - lasers, electronics, propulsion systems
- Cryogenic temperature regime
 - that's where the science is headed
- Increasingly integrated designs (e.g., NGST)
- Fleets of micro/nano spacecraft have special problems
 - small C_p and need for common design (e.g., ST5)
- Challenging thermal sinks (e.g., Solar Probe, ULDB flights)